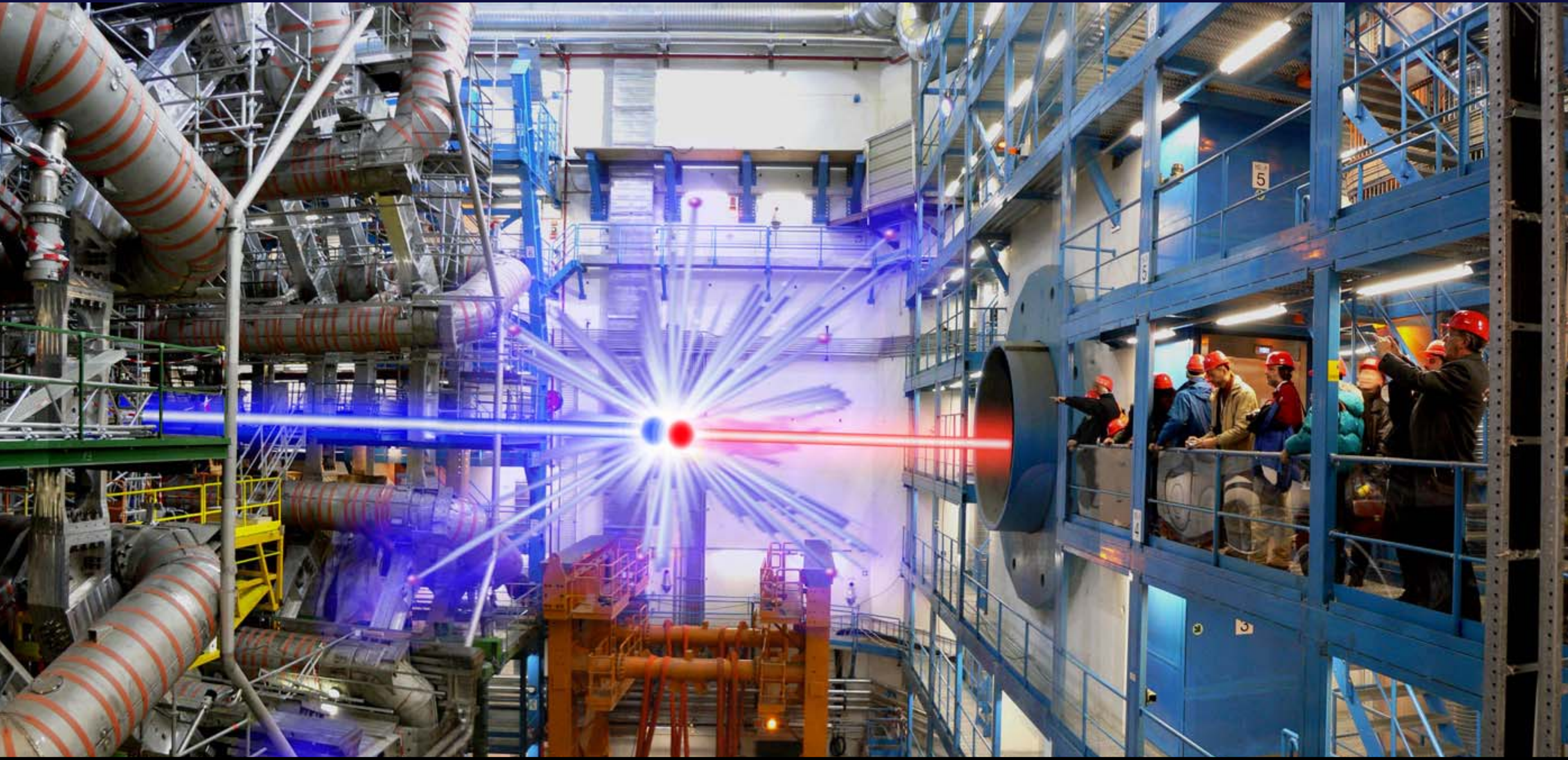
Introduction to Particle Physics



HEP Workshop

November 6^{th}-10^{th} 2006

VILNIUS

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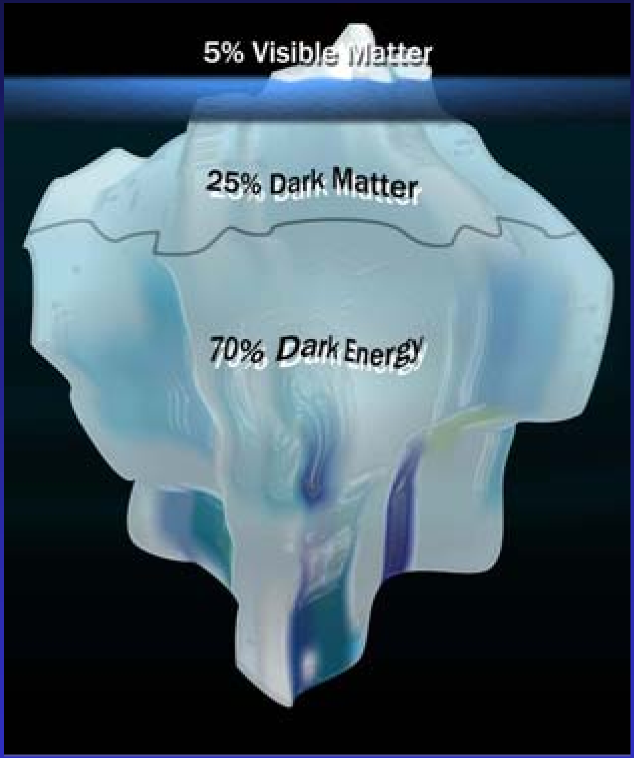
ÖAW Austrian Academy of Sciences

Some "Hot Questions" of Particle Physics (and Cosmology)

- What is the origin of the fundamental particles' mass? (is it an interaction with the higgs?)
- Why is there so much more matter than anti-matter? (What are the symmetries of the universe, and which ones are violated?)
- What is dark matter and dark energy?
- Is there a universal "super-symmetry"? (which implies the existence of a whole "mirror world" of unknown, supersymmetric particles)
- Can all known forces be unified (Grand Unification)?
- …?



Introduction to Particle Physics

Overview

Unit I: The Particle Zoo
Unit II: Accelerators & Detectors
Unit III: Symmetries
Unit IV: The Standard Model (& beyond)
Unit V: CP-Violation in B-Decays (BELLE)

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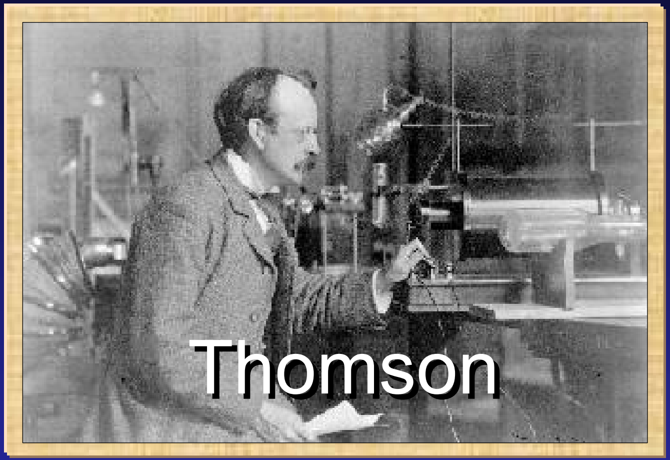
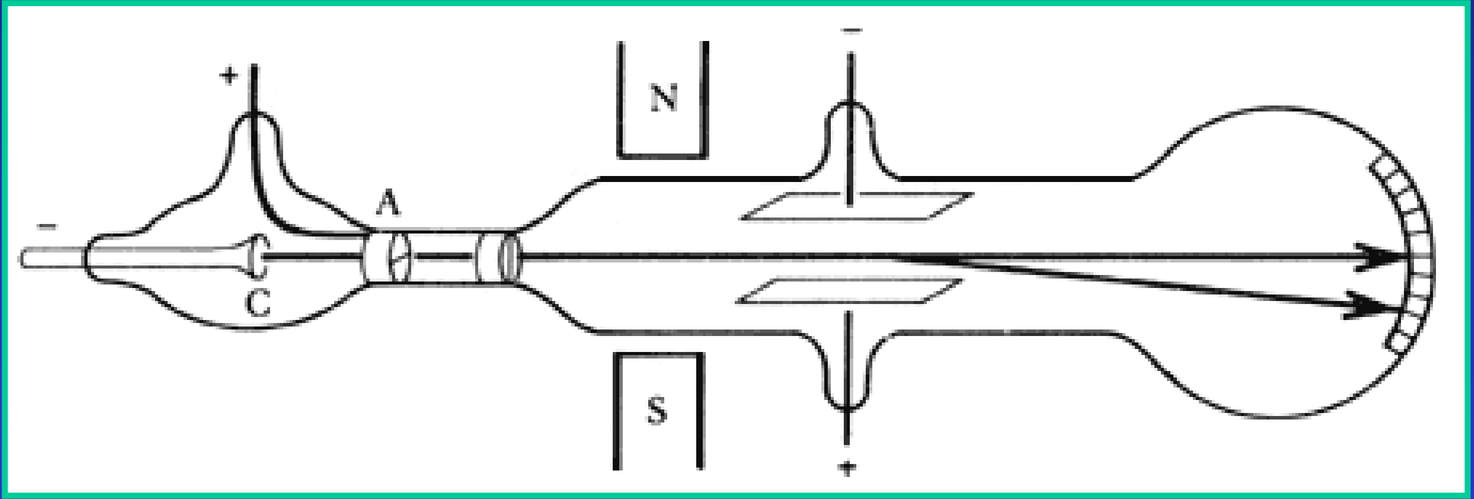
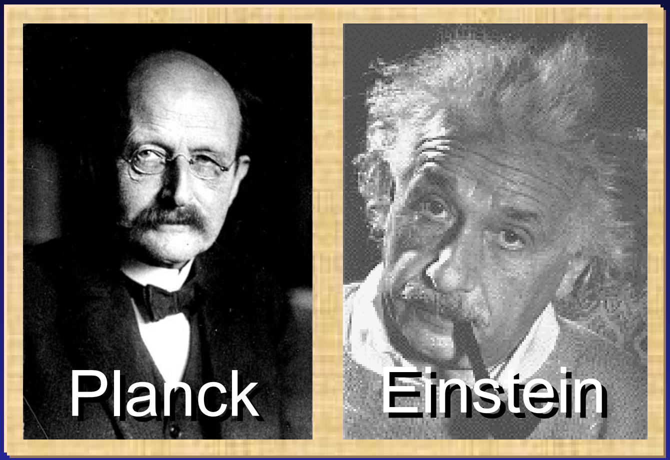
e^- the electron

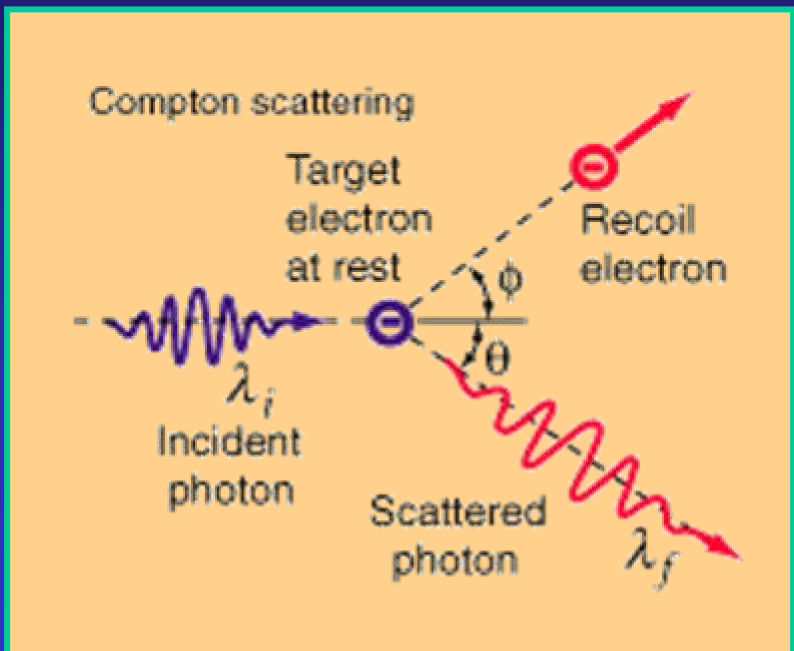


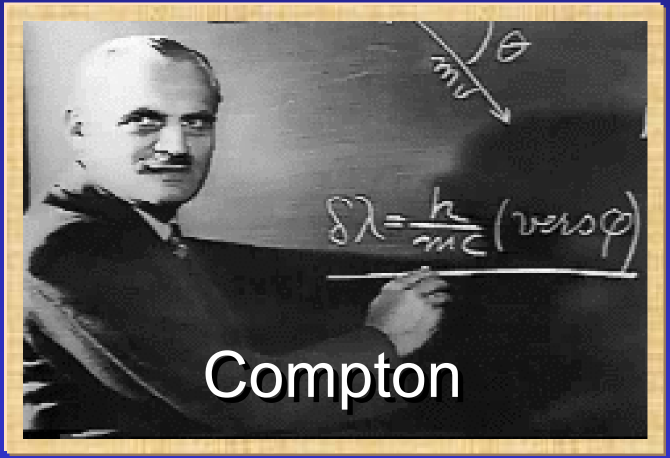


1897

the photon

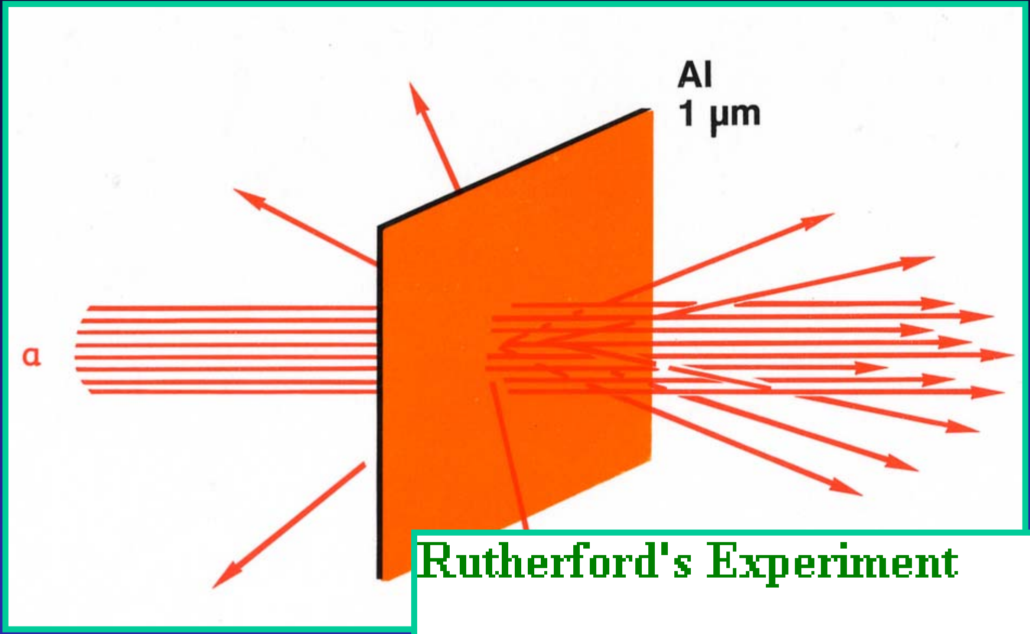


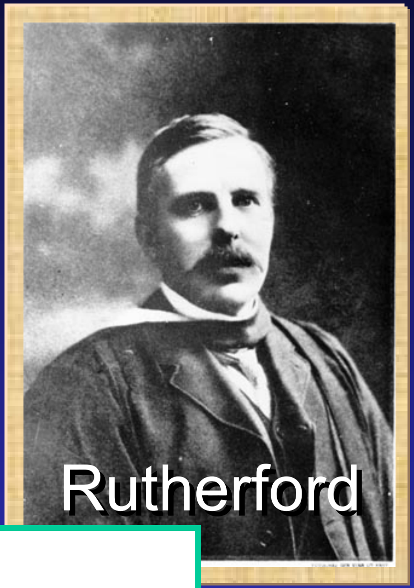


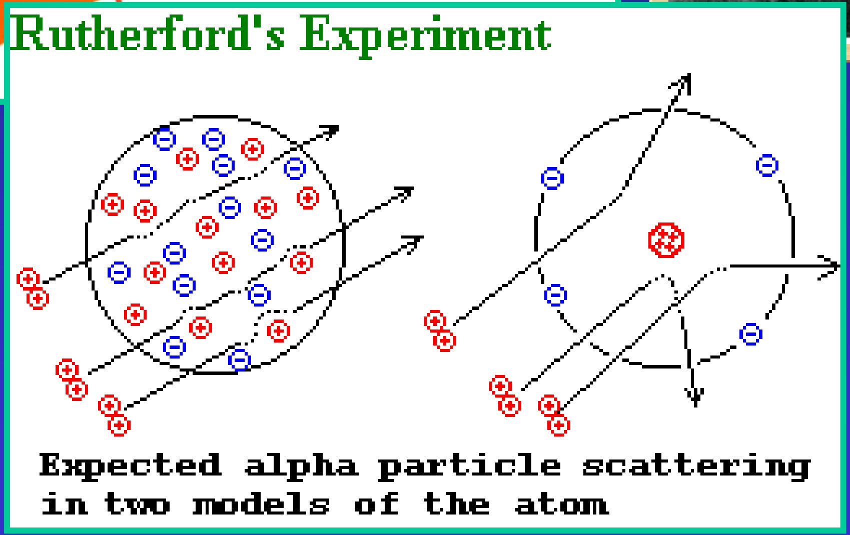


1897 1900-1924

p the proton


Al
1 µm
α

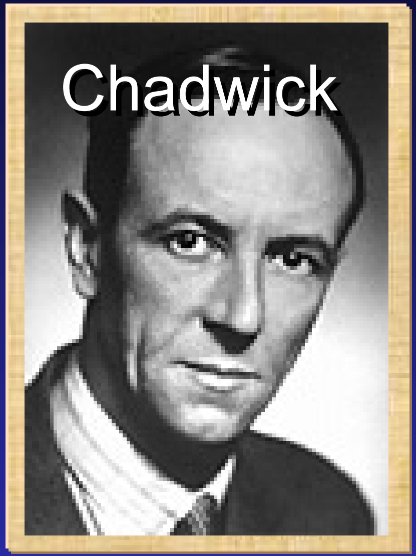

Rutherford

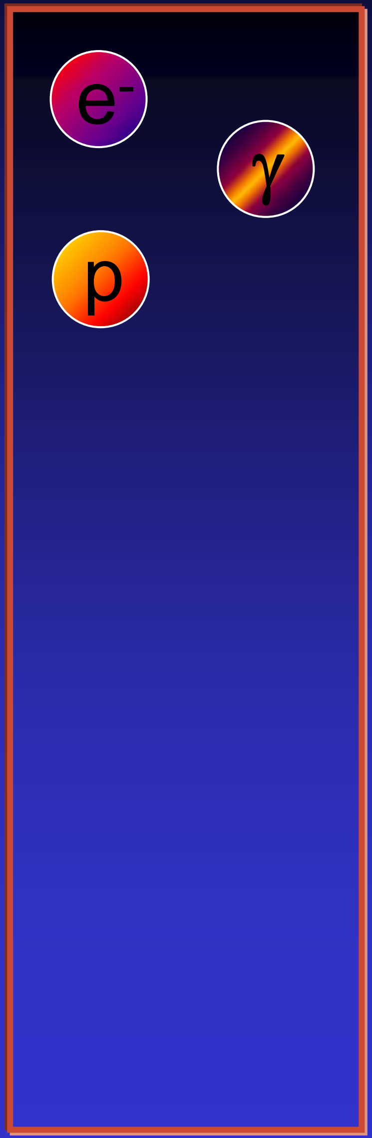

Rutherford's Experiment
Expected alpha particle scattering
in two models of the atom

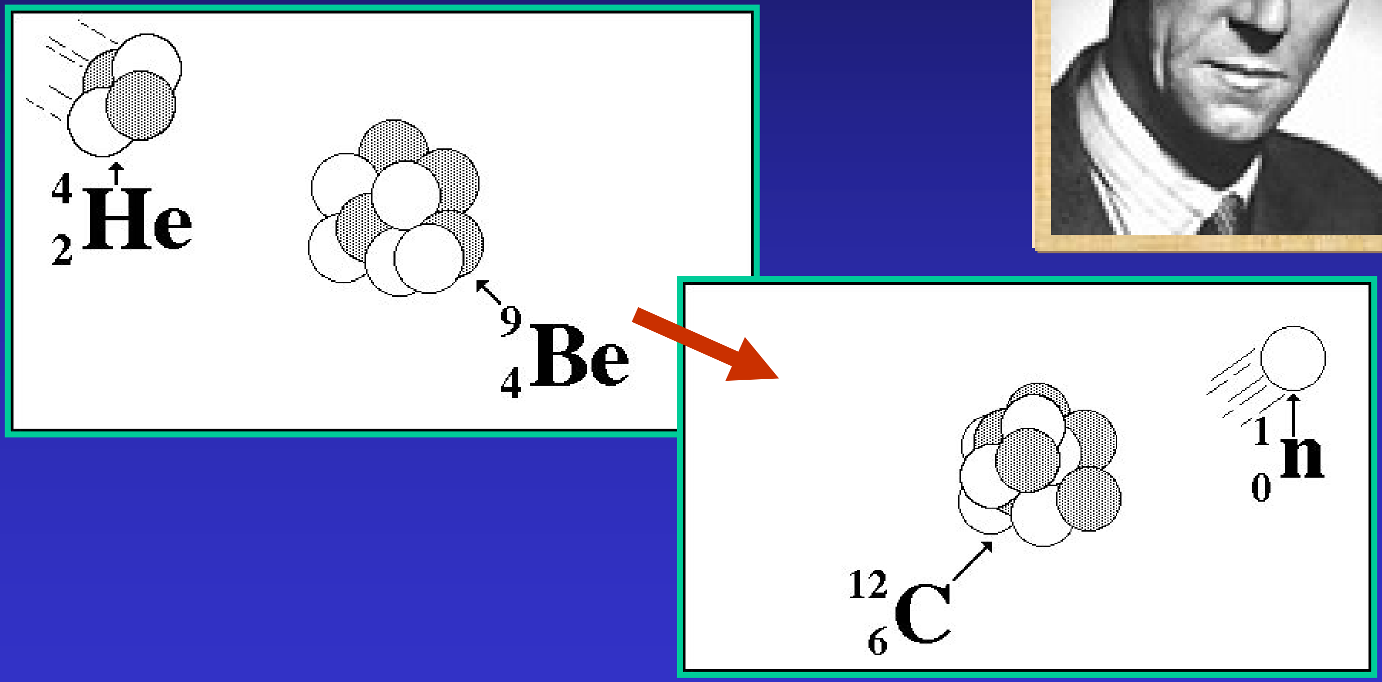

e-
γ

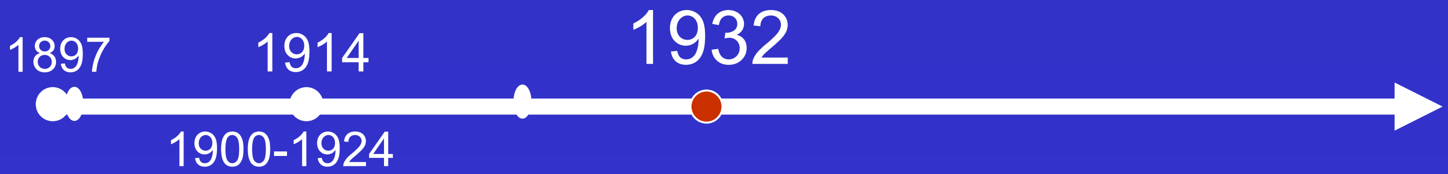

1897
1914
1900-1924

n the neutron

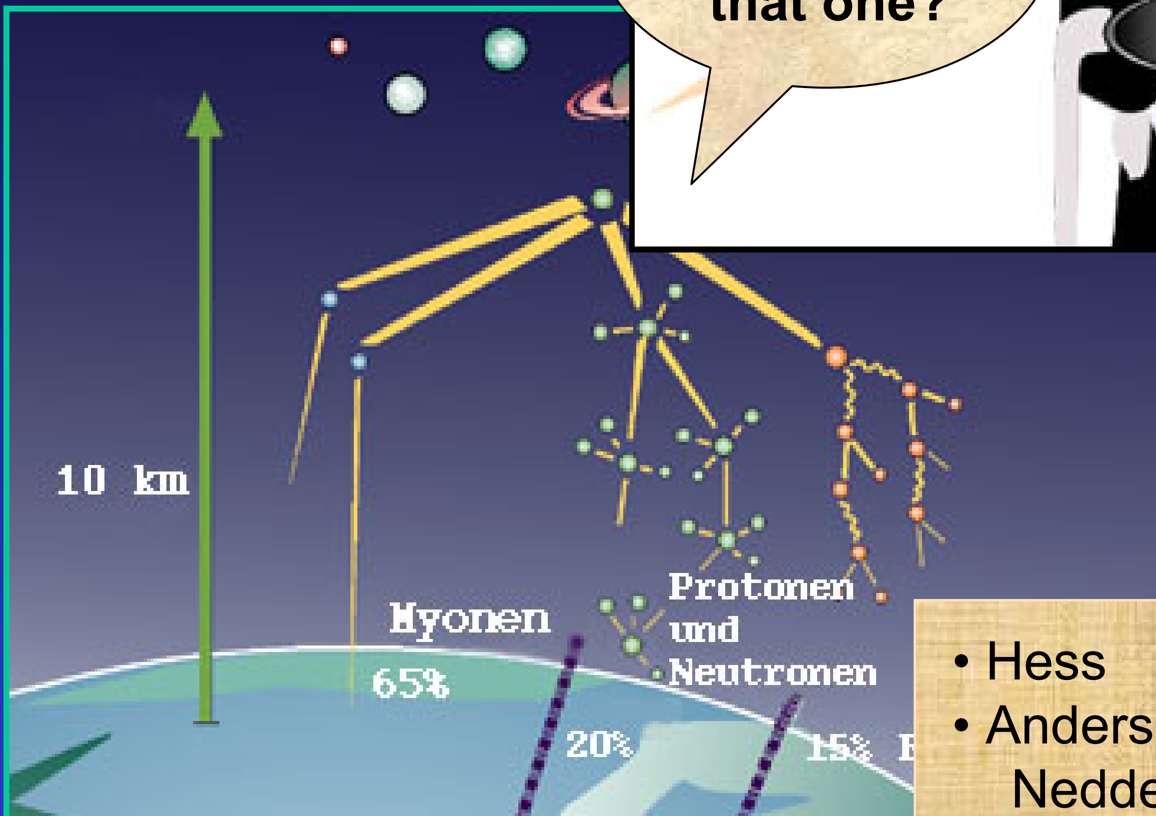


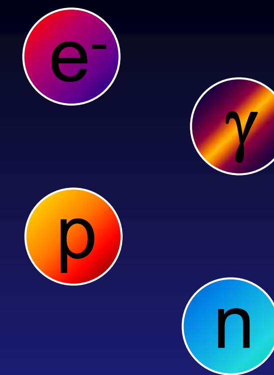


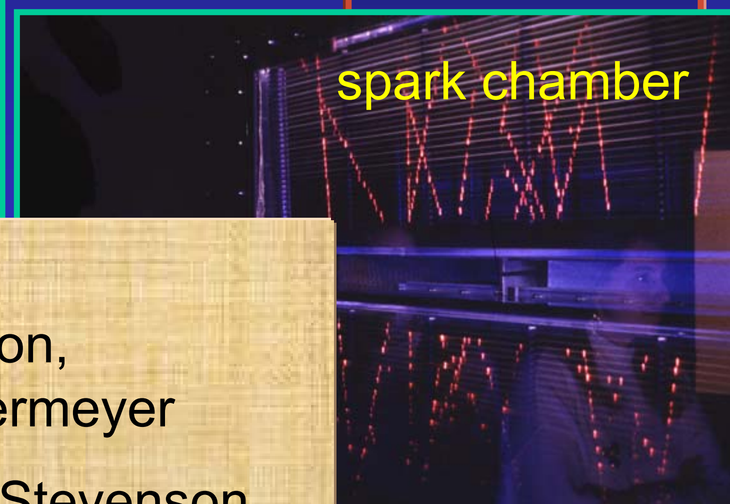




μ the muon



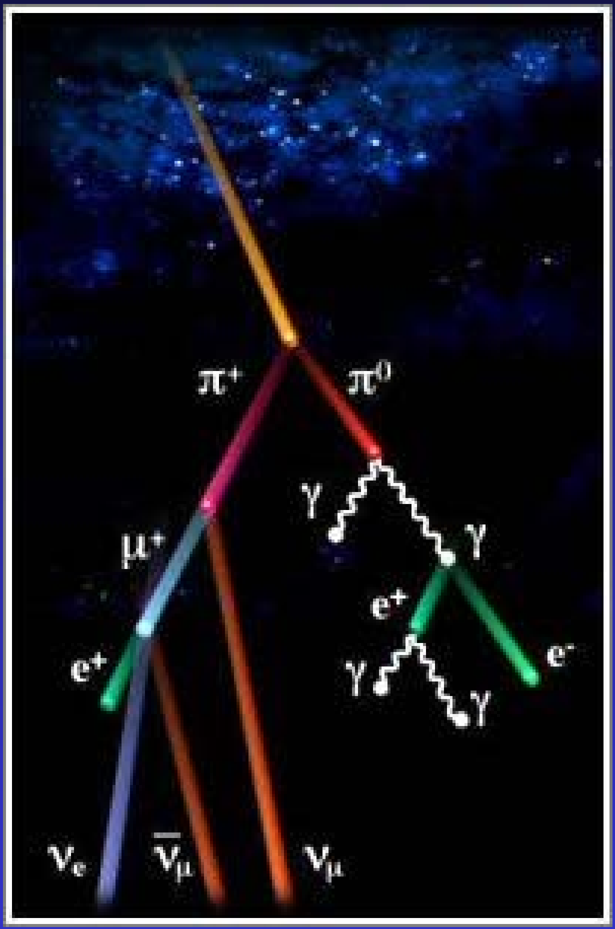




- Hess
- Anderson, Neddermeyer
- Street, Stevenson

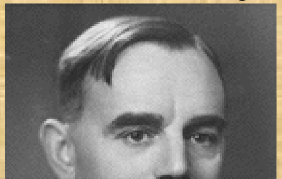
1897 — 1900-1924 — 1914 — 1932 — **1937**

π the pion



prediction

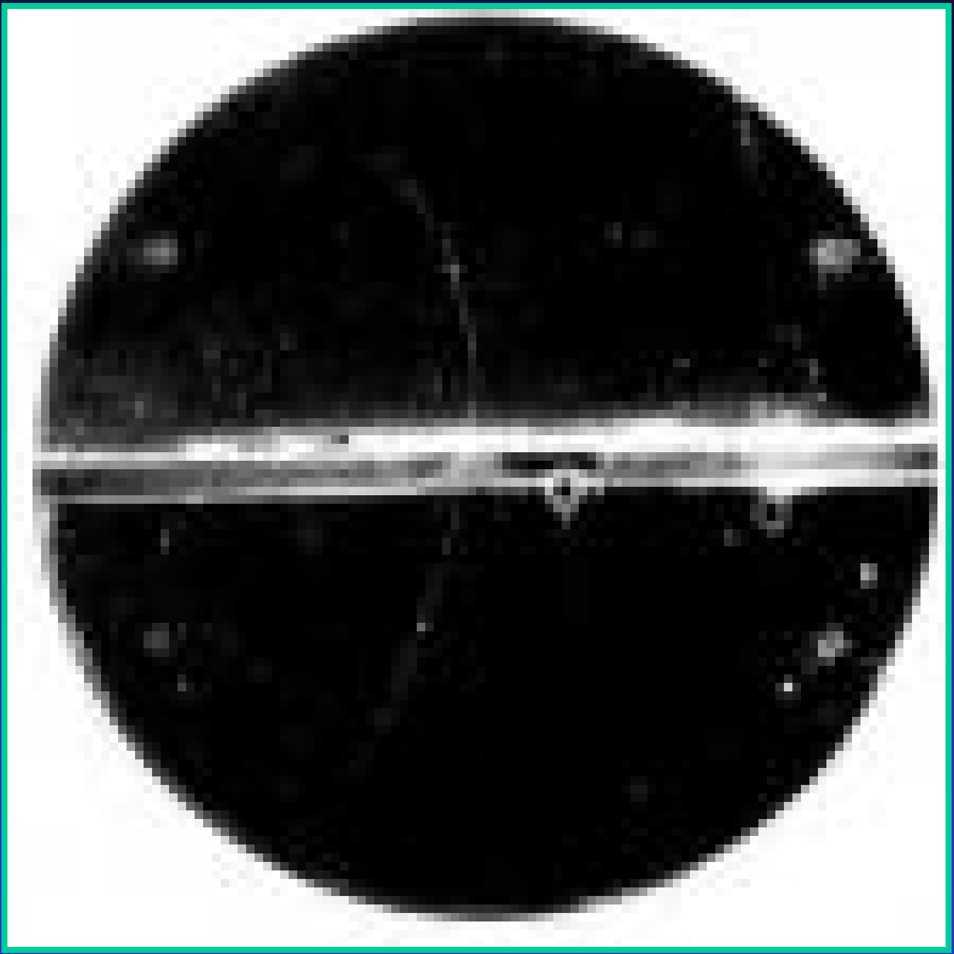
discovery



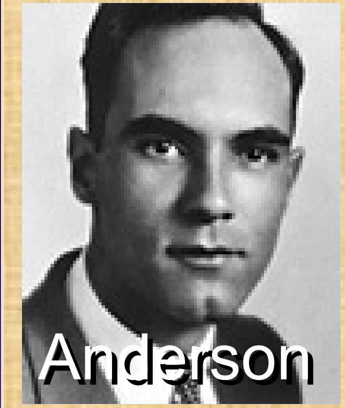
e⁻ γ p n μ

1897 1900-1924 1914 1932 1937 **1947**

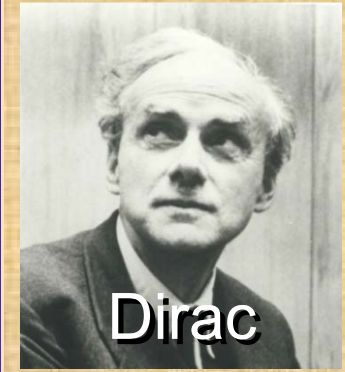
e^+ the positron (anti-matter)



discovery



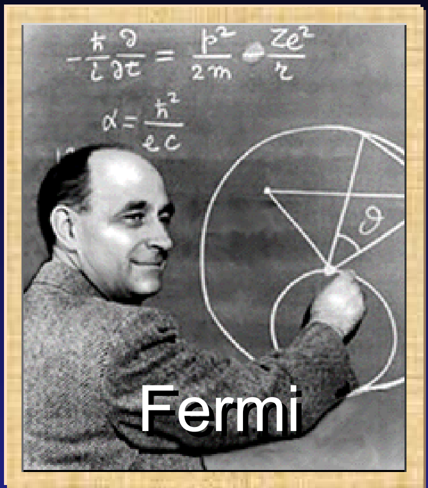
prediction

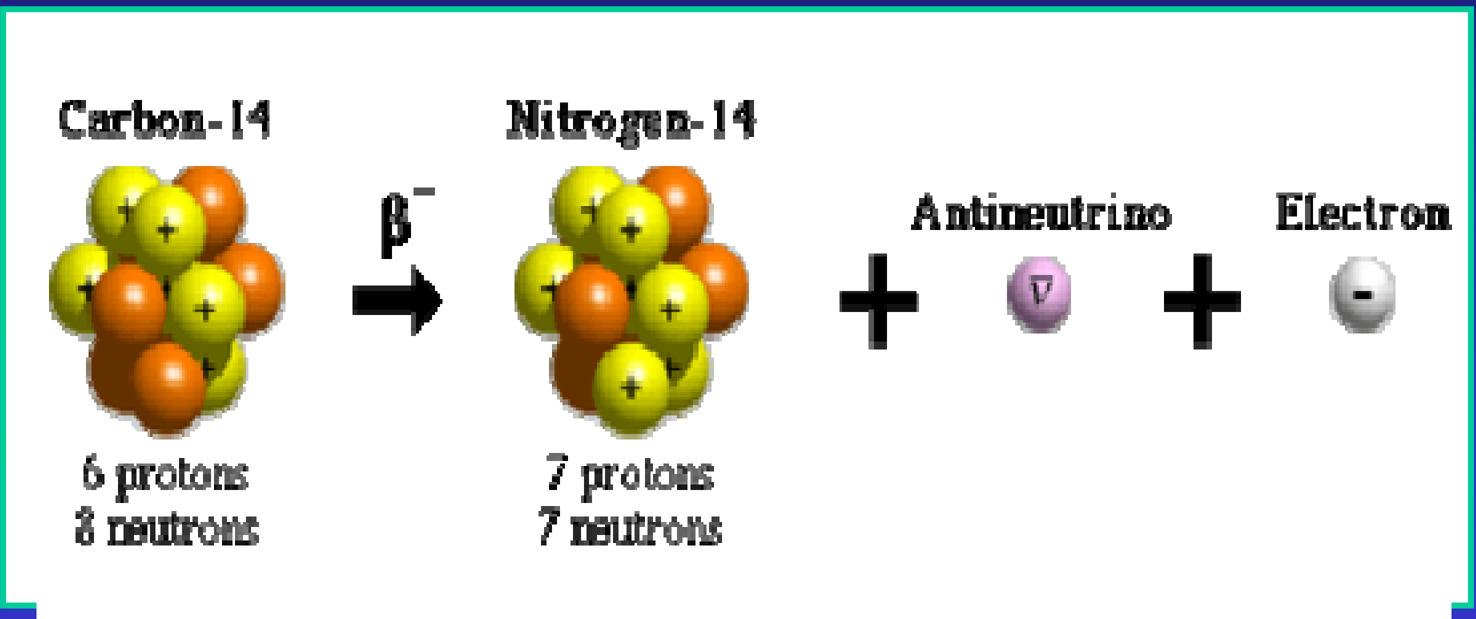


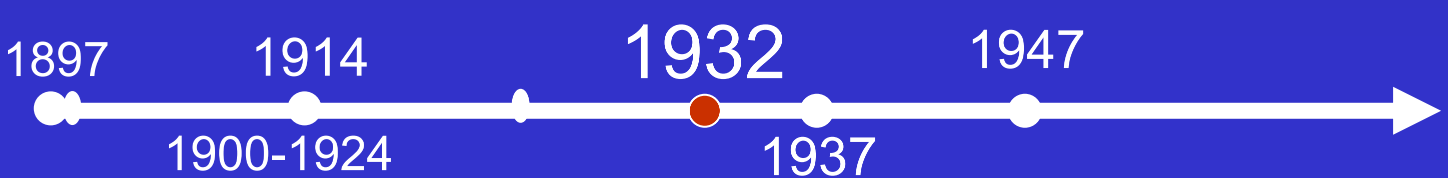
e^- γ p n μ π

1897 1900-1924 1914 **1932** 1937 1947

ν the neutrino





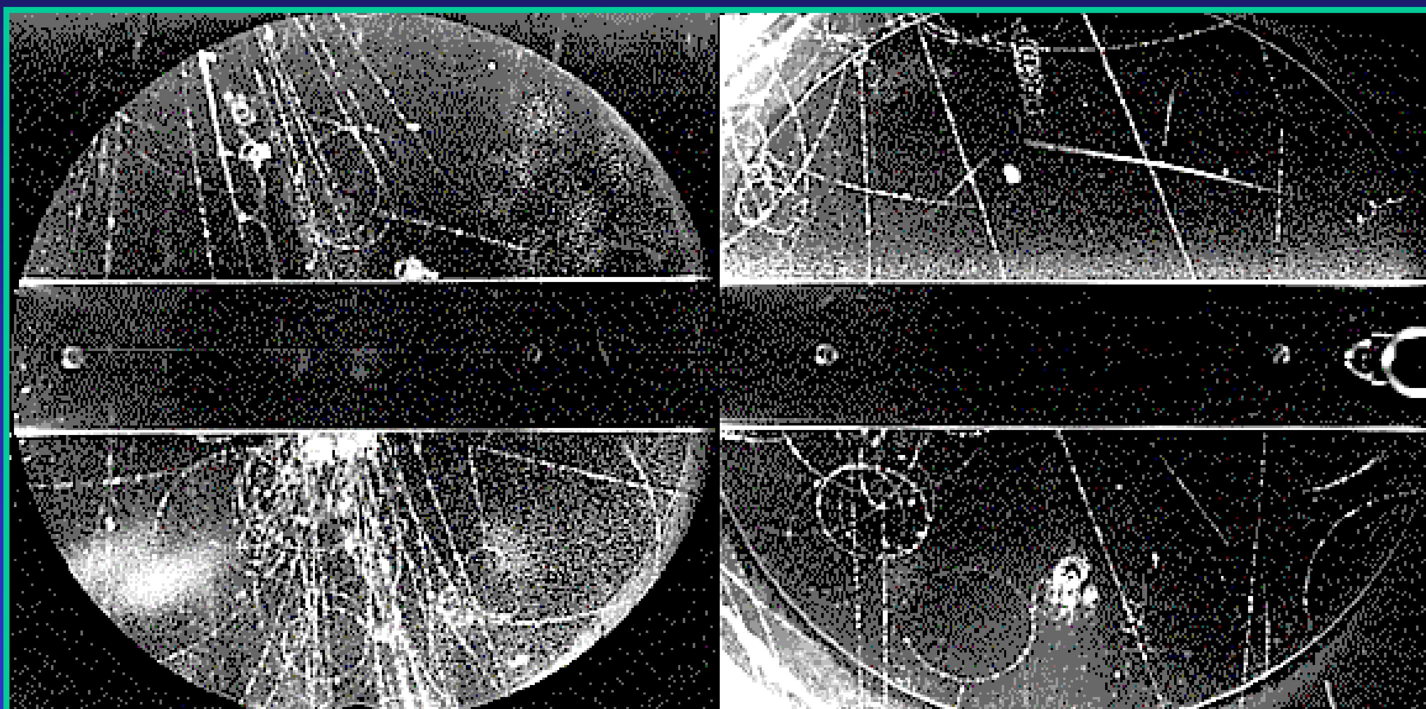


e^- γ p n μ π e^+

Λ
K
Σ

strange particles

Rochester,
Butler,
...

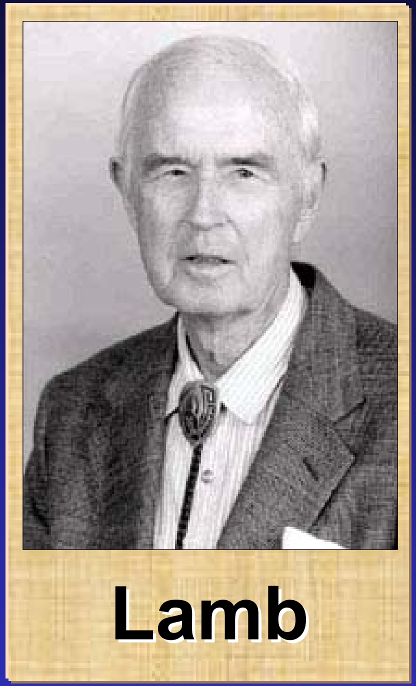


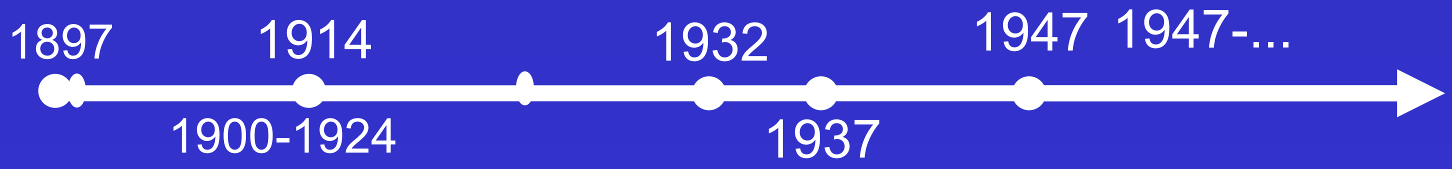
e^- γ p n μ π e^+ ν

1897 1900-1924 1914 1932 1937 1947 **1947-...**

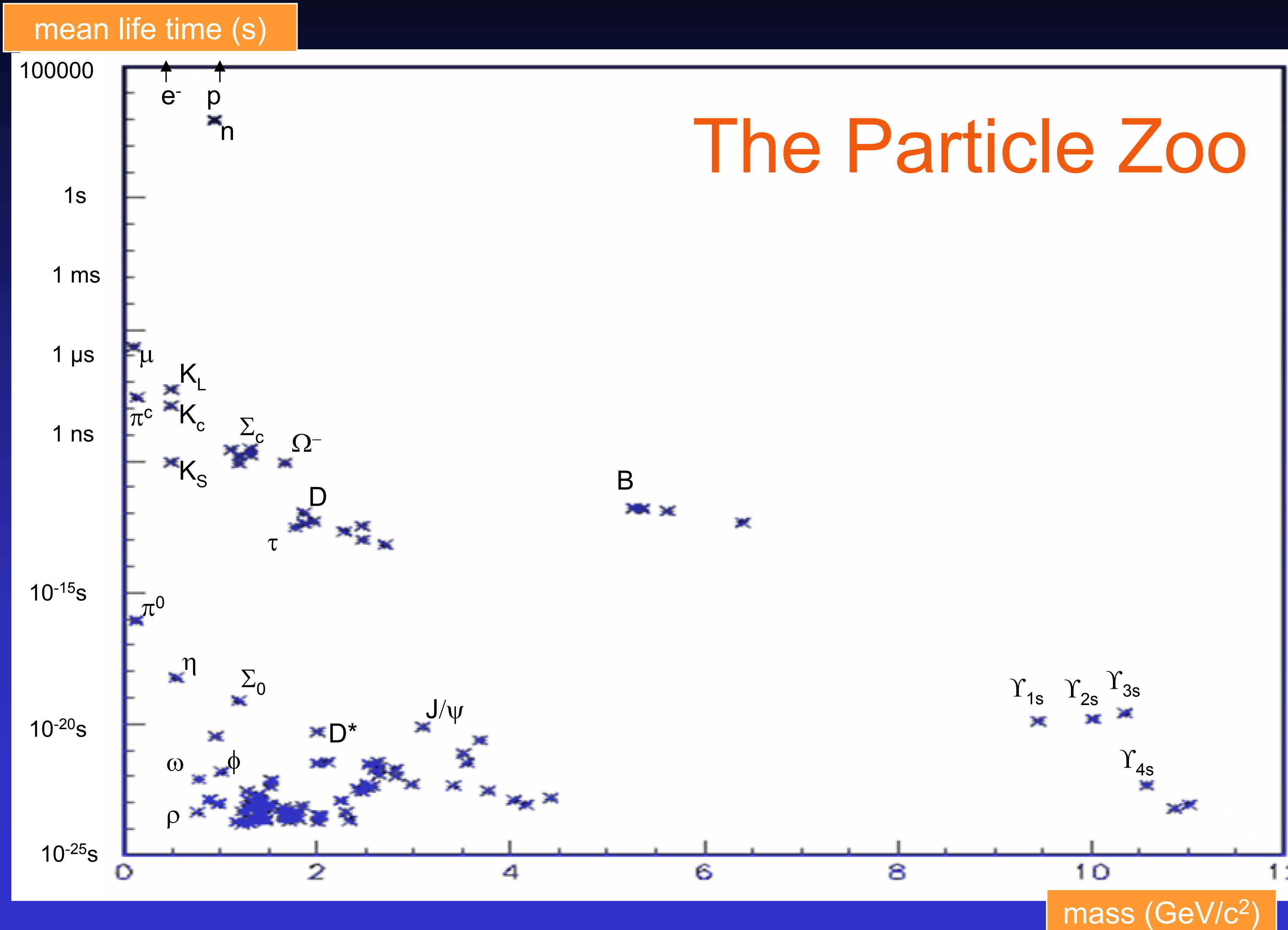
Willis Lamb, in his Nobel prize acceptance speech 1955, expressed the mood of the time:

„I have heard it said that the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine.“





The Particle Zoo

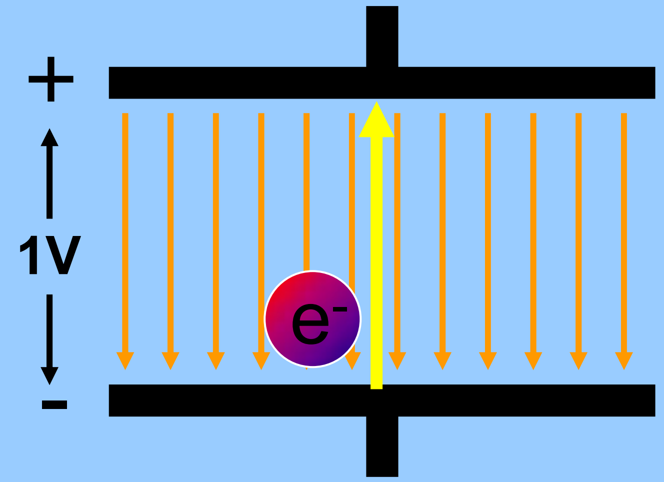


side note:

Natural Units in Particle Physics

- the fundamental constants c and $\hbar$ are set to 1 and are dimensionless
- the only remaining dimension is that of energy, which is measured in units of eV
- all other dimensions can be expressed in powers of [eV]:

the electron volt (eV)

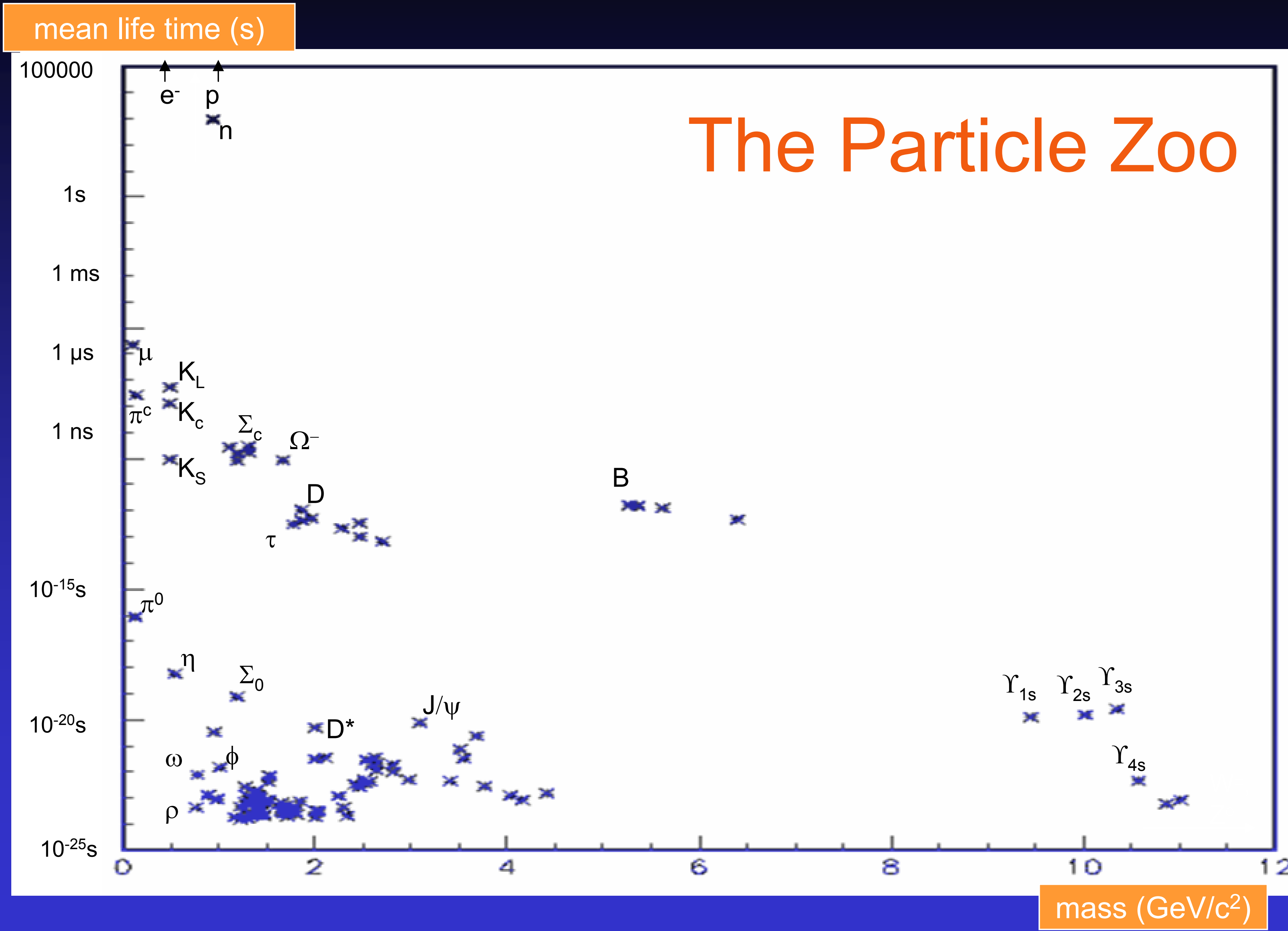


1GeV = 10^9 eV

$$E = mc^2$$

energy	[eV]	1 eV	$= 1.60328 \cdot 10^{-13}$ J
length	[eV^{-1}]	1 $c\hbar$/eV	$= 1.97327 \cdot 10^{-7}$ m
time	[eV^{-1}]	1 $\hbar$/eV	$= 6.58212 \cdot 10^{-16}$ s
mass	[eV]	1 eV/c^2	$= 1.78266 \cdot 10^{-36}$ kg
temperature	[eV]	1 eV/k	$= 1.16044 \cdot 10^{4}$ K

The Particle Zoo



Looking for some order in the chaos...

1. properties of particles:

- order by mass (approximately, rather to be seen historically) :

leptons (greek: „light“)	electrons, muons, neutrinos, ...
mesons („medium-weight“)	pions, kaons, ...
baryons („heavy“)	proton, neutron, lambda, ...

- order by charge:

neutral	neutrons, neutrinos, photons ...
±1 elementary charge	proton, electron, muon, ….
±2 elementary charge	Δ^{++}, Σ_c^{++}

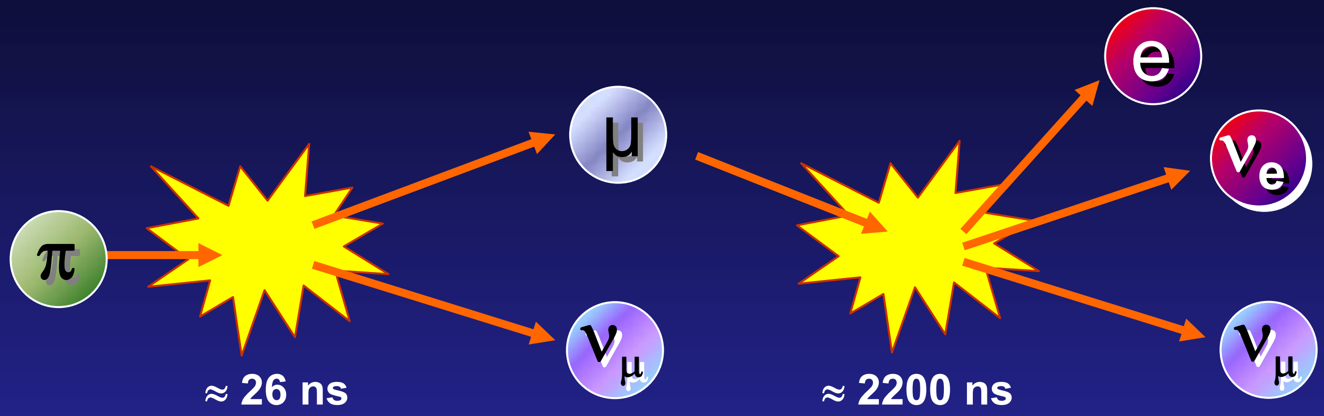
- order by spin:

fermions (spin ½, 1½, ...)	electrons, protons, neutrinos, …
bosons (spin 0, 1, …)	photons, pions, …

- order by „strangeness“, parity, ...

Observing particle decays:

Decay



Looking for some order in the chaos...

2. conservation laws for particle decays:

- conservation of energy:

  $n \rightarrow p + \ldots$ but not $\pi^0 \rightarrow \pi^+ + \ldots$

- conservation of charge:

  $n \rightarrow p + e^- + \ldots$ but not $n \rightarrow p + e^+ + \ldots$

- conservation of lepton number:

  $n \rightarrow p + e^- + \bar{\nu}$ but not $n \rightarrow p + e^- + \nu$

- conservation of baryon number:

  $n \rightarrow p + \ldots$ but not $n \rightarrow \pi^+ + \pi^- + \ldots$

- conservation of strangeness (only in „fast“ processes)

  fast $K^* \rightarrow K\pi$ but only “slow” $K \rightarrow \pi\pi$

How can these patterns be understood?

→ **Unit III (TUE): Symmetries**
→ **Unit IV (WED): The Standard Model**

but first: how can we study elementary particles?

→ **Unit II (today): Accelerators & Detectors**

- END of Unit I -

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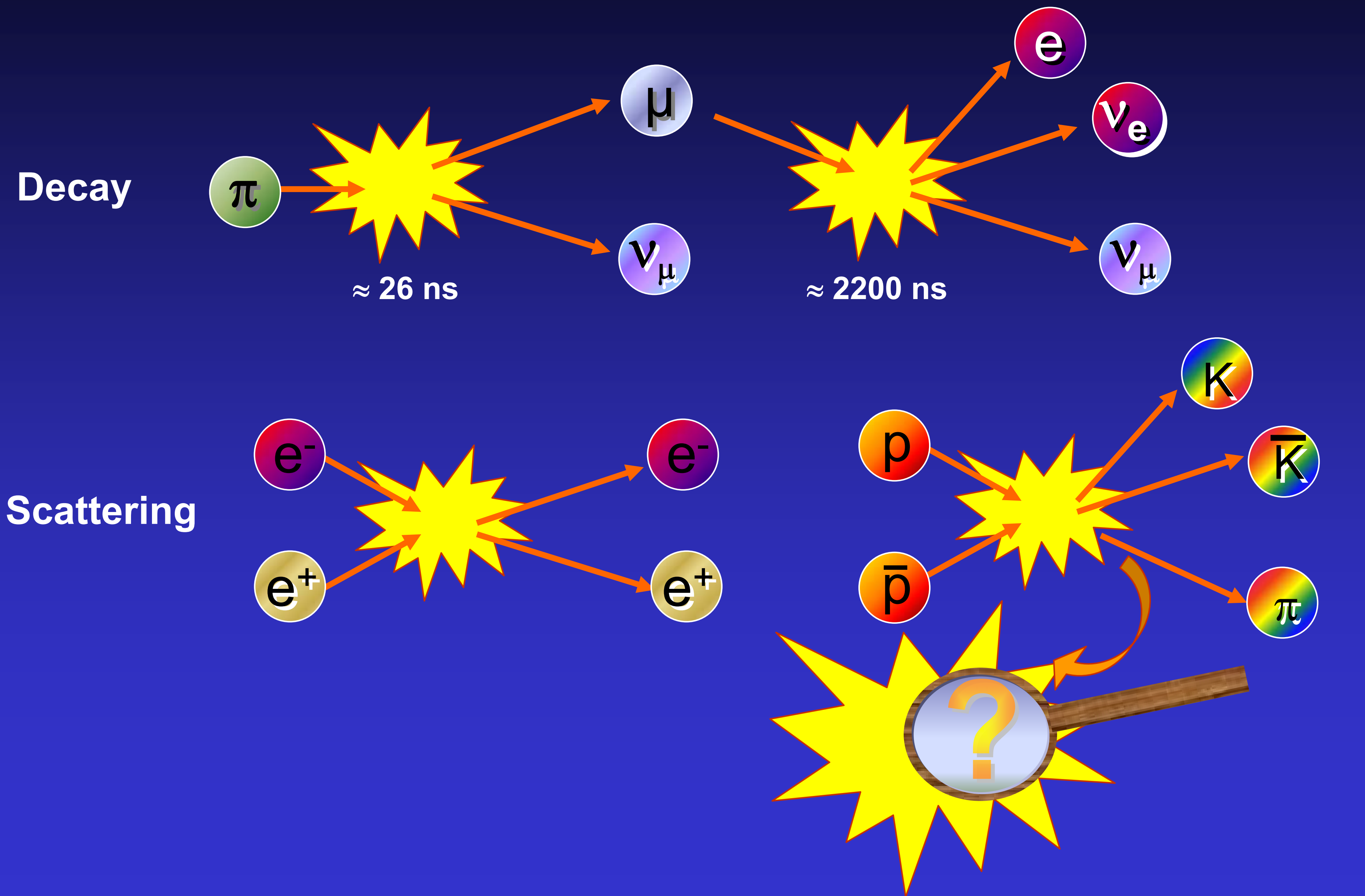
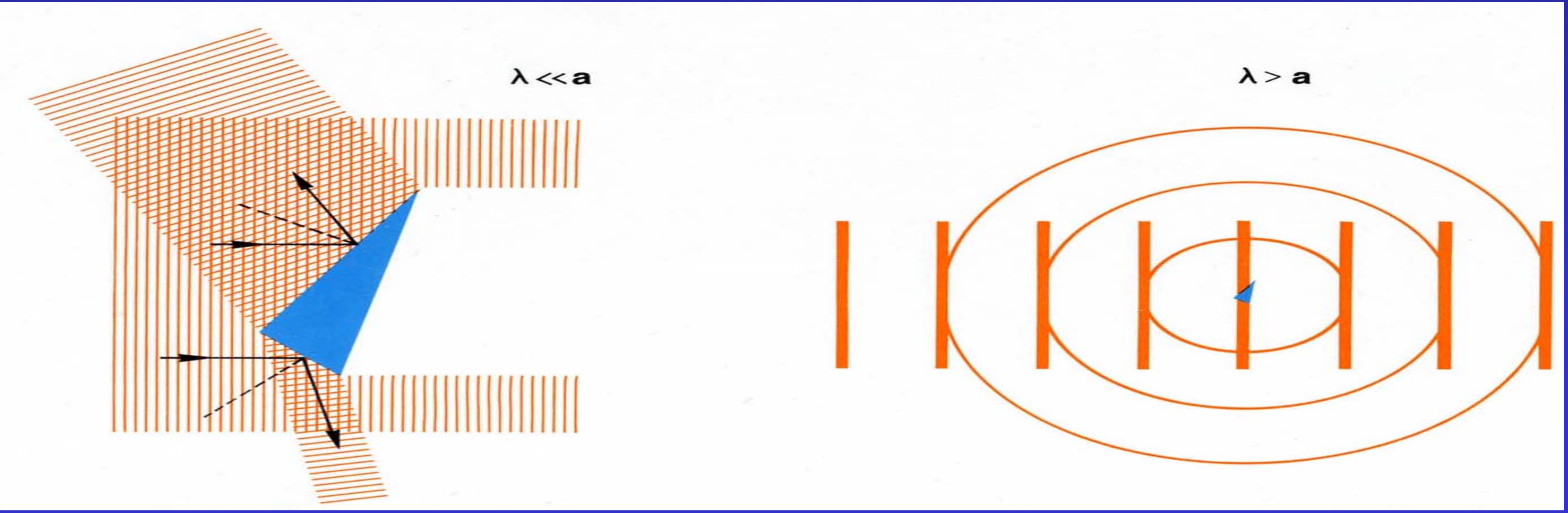
Observing particle decays and interactions



Using particles as probes

- since about 80 years, accelerated (high-energetic) particles are used as probes for the examination of samples
- this is actually a method copied from nature: for our eye-sight, photons are used as „probes“. „Seeing“ is interpreting their interaction with matter.
- in the microcosm, where the size of structures is similar to the „size“ (wavelength) of the used probes, we get diffraction, thus loose information about shape:

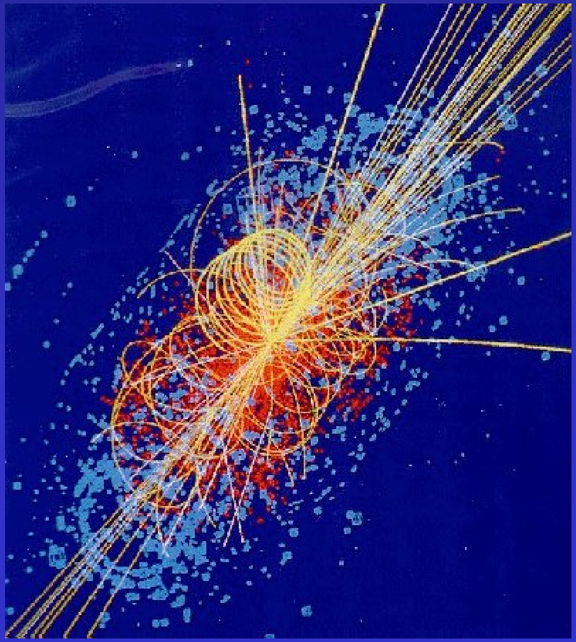


Particle accelerators

- electron accelerators: very short-waved particle probes, shot directly at the „target“ probe; most widely-known example: electron microscopes

- at even higher energies of the probes, new particles can be produced – short-lived particles, which existed shortly after big bang, can be „revived“: a „mini big bang“ in the lab!

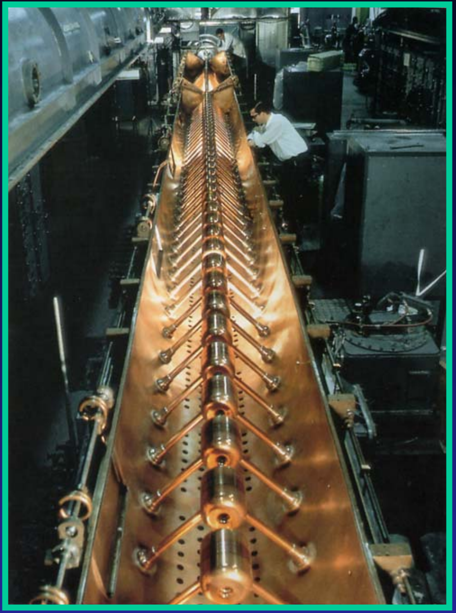
- to get even closer to big bang: build colliders, where accelerated particles collide head-on

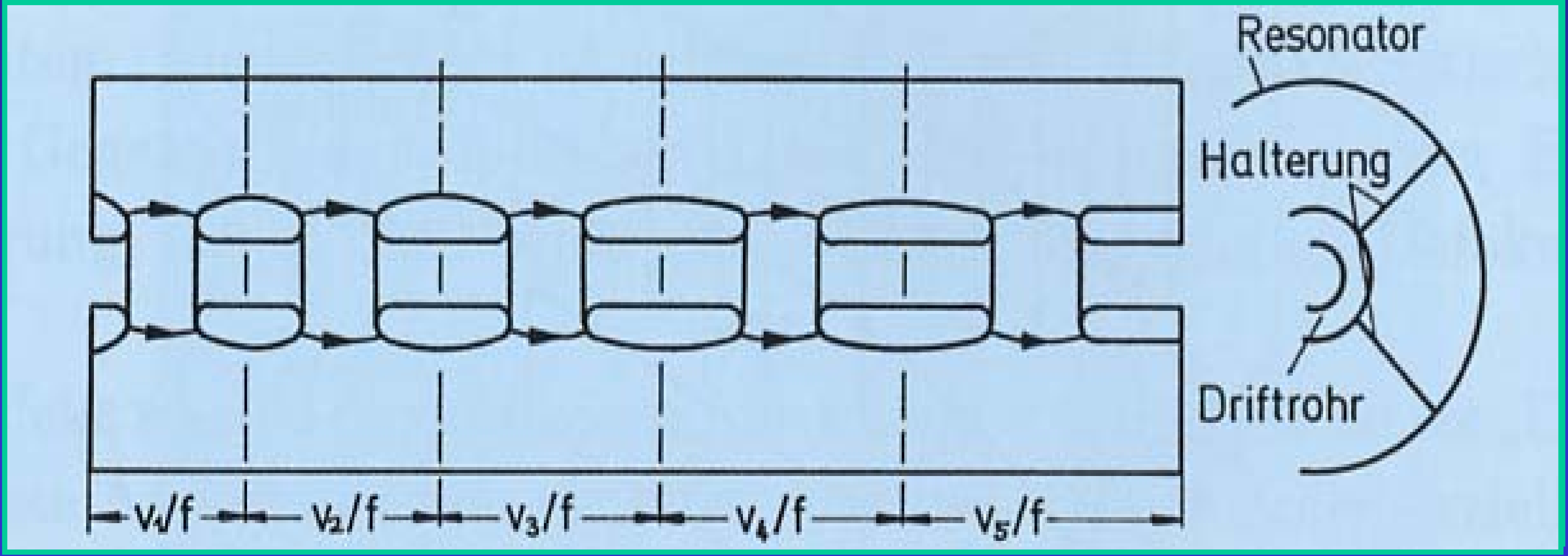


Particle accelerators

• in the early times: electro-static accelerators (cascade generator, Van-de-Graff generator)

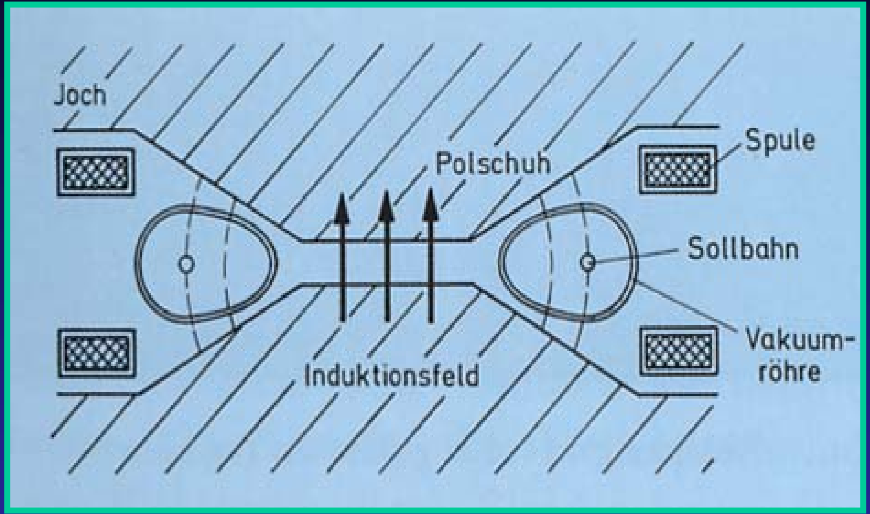
• in parallel, high-frequency linear accelerators have been developed



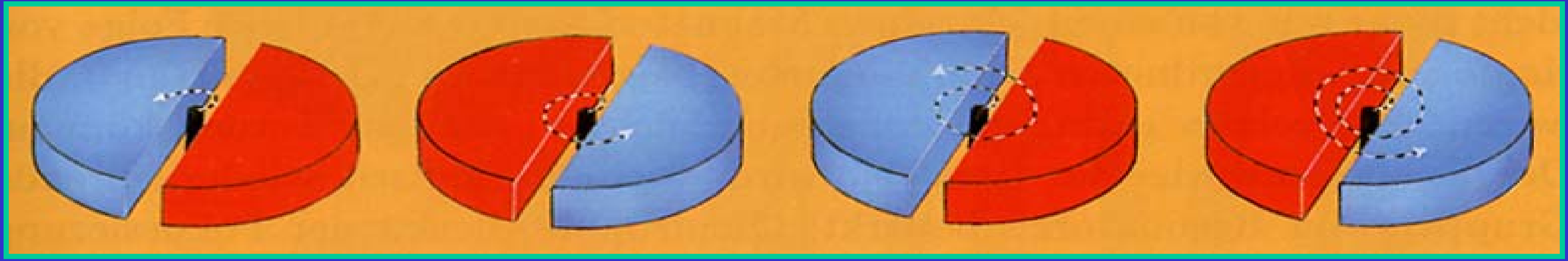


Particle accelerators

• the betatron, a „free-flight transformator“: a magnet field (which holds particles in an orbit) is increased with time, thus producing a circular electric induction field which accelerates the particles



• the cyclotron, peak of development of accelerator physics in the 1920ies: a charged particle circulates in a magnetic field, and is accelerated by switched electro-static fields. At non-relativistic energies, the rotational frequency is independent of the momentum (or energy) of the particle, only the orbit radius increases with time → spiral path

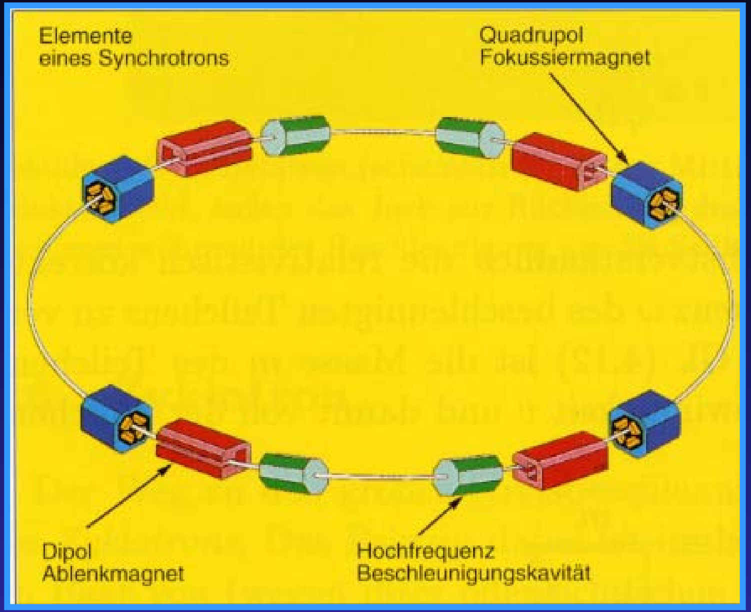


Particle accelerators

the synchrotron is the advancement of the cyclotron to relativistic energies. It consists of several modules which take over different tasks:

- bending magnets force particles on their circular path
- high-frequency cavities take care of the acceleration
- focussing magnets keep the particle beams together

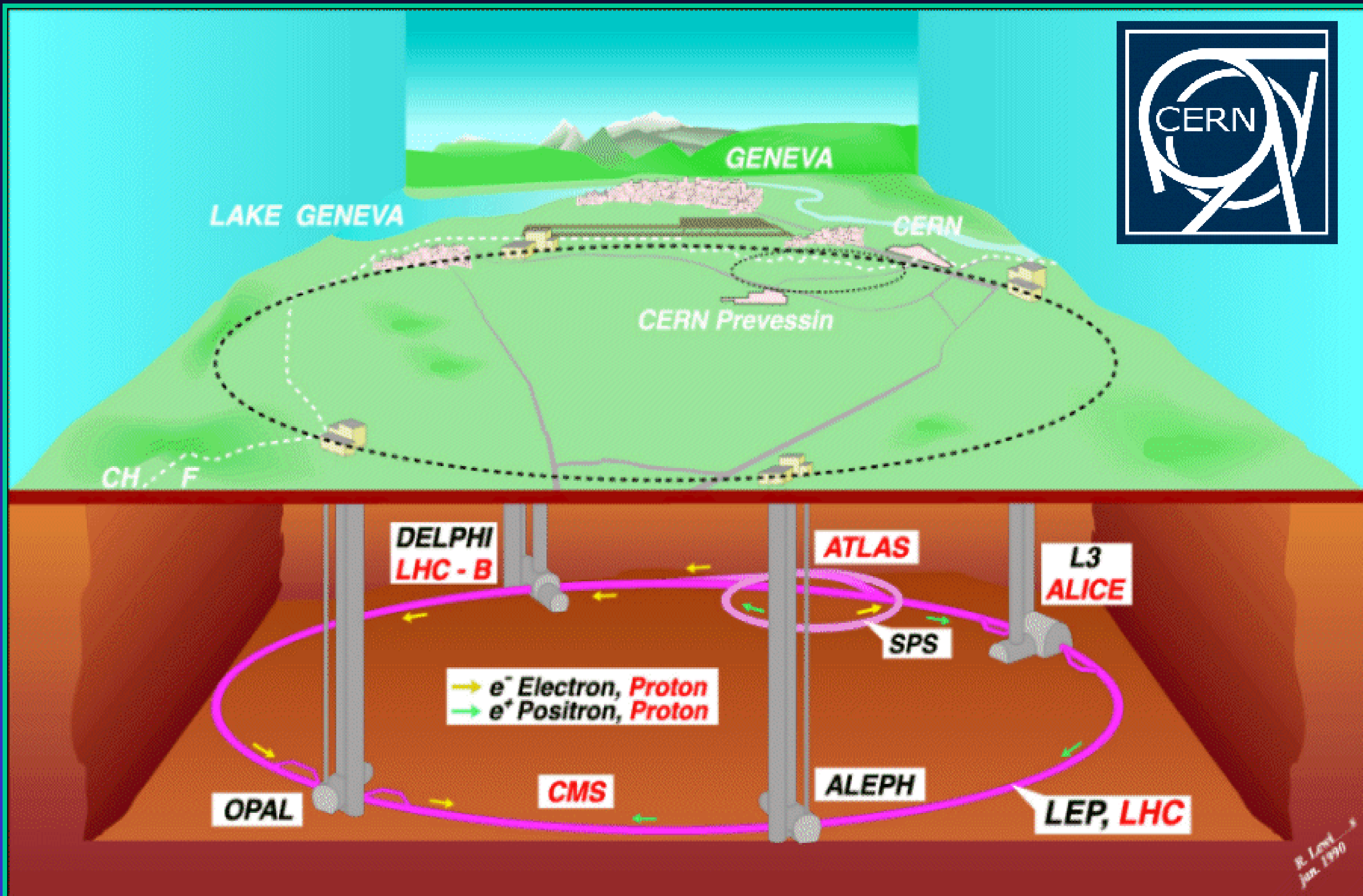
The world's largest electron-positron collider is the LEP, built in the 1980ies and used until 2000 at CERN, Geneva reaching ~200 GeV of energy. It is now being replaced by the LHC, which collides protons at energies of 14 TeV



Particle accelerators

accelerator	particles	E_{beam}	started	**luminosity** [10^{-30} cm^{-2} s^{-1}]
TEVATRON	$p\,\bar{p}$	**2 x 900 GeV**	1987	25
PEP II	$e^+ e^-$	**10,5 GeV**	1999	5000
KEK B	$e^+ e^-$	**10,5 GeV**	1999	13 000
HERA	$p\, e^{\pm}$	**26 + 820 GeV**	1992	15
LHC **(being built)**	p p	**2 x 7000 GeV**	2007/8	>10 000


CERN


CERN
GENEVA
LAKE GENEVA
CERN
CERN Prevessin
CH
F
DELPHI
LHC - B
ATLAS
L3
ALICE
SPS
e⁻ Electron, Proton
e⁺ Positron, Proton
OPAL
CMS
ALEPH
LEP, LHC

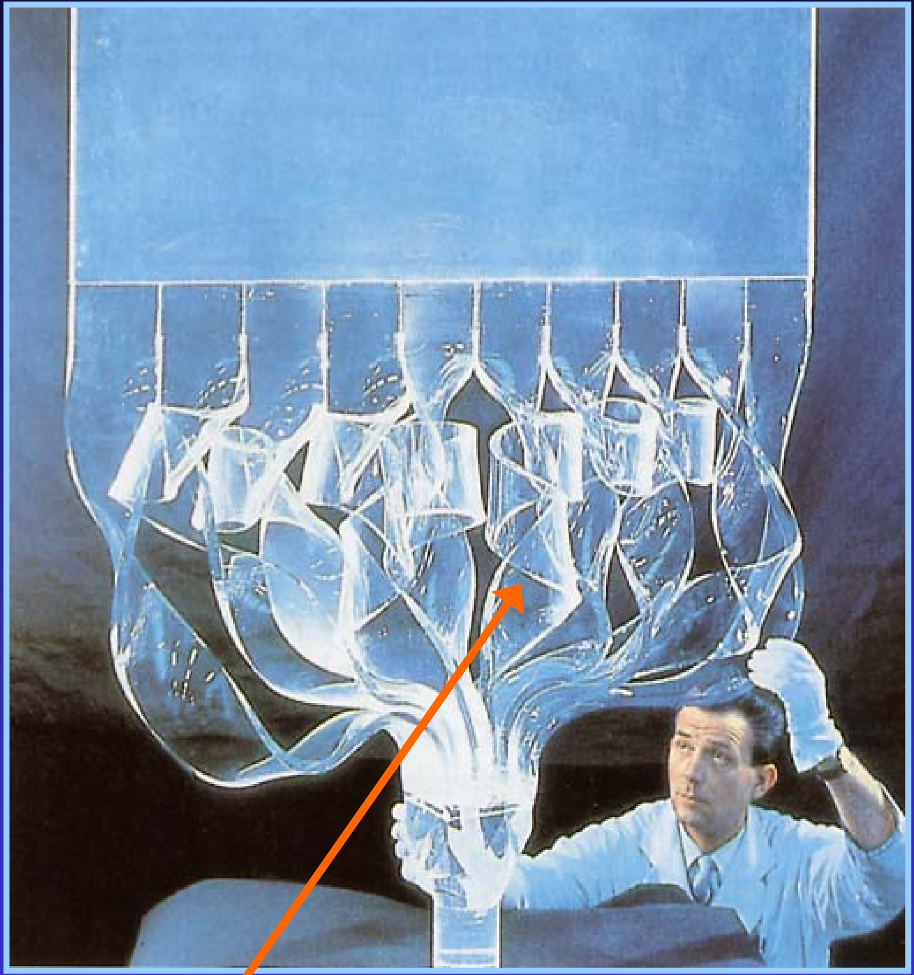
Particle detectors

historical detectors:

- scintillator counters
- wire counters
- Wilson‘s cloud chambers
- emulsions

scintillators

- simple
- fast
- still in use

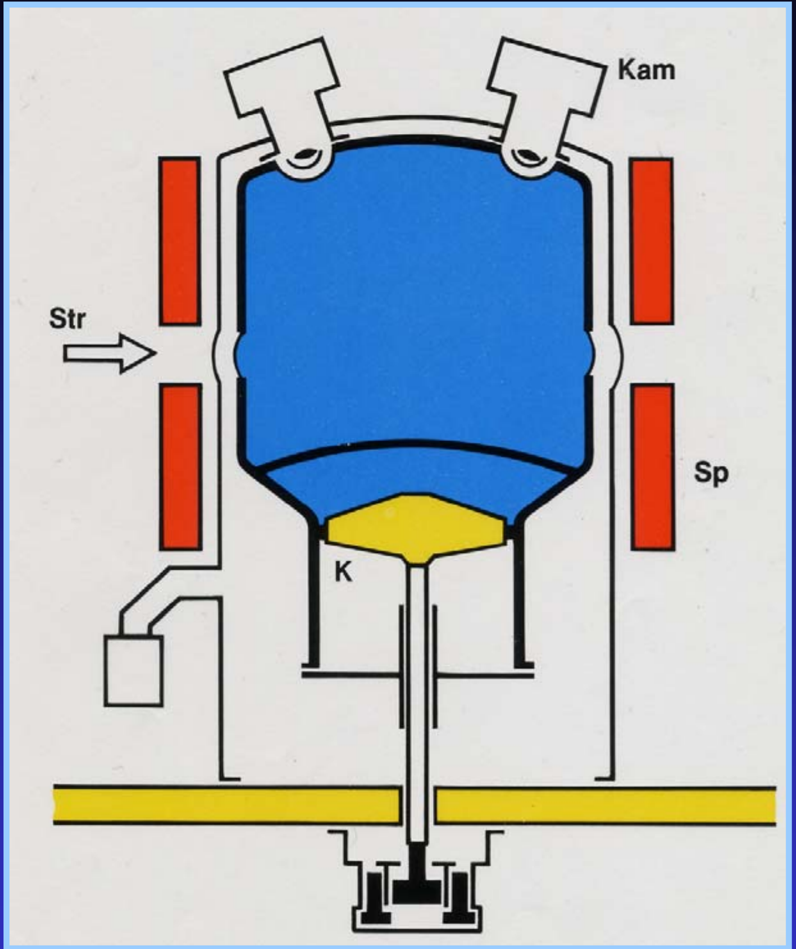


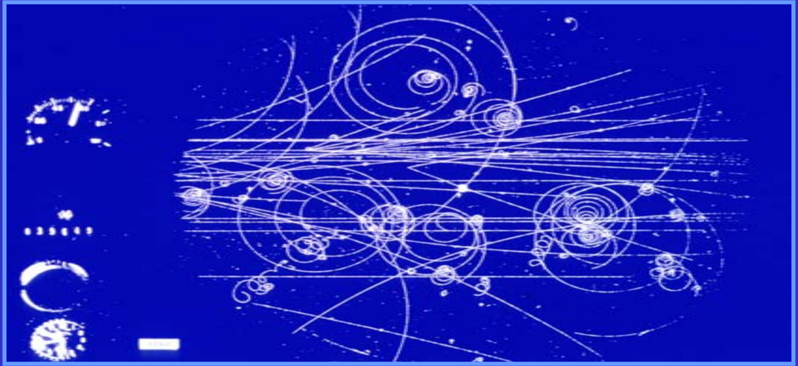
light guide structures

Particle detectors

bubble chamber:

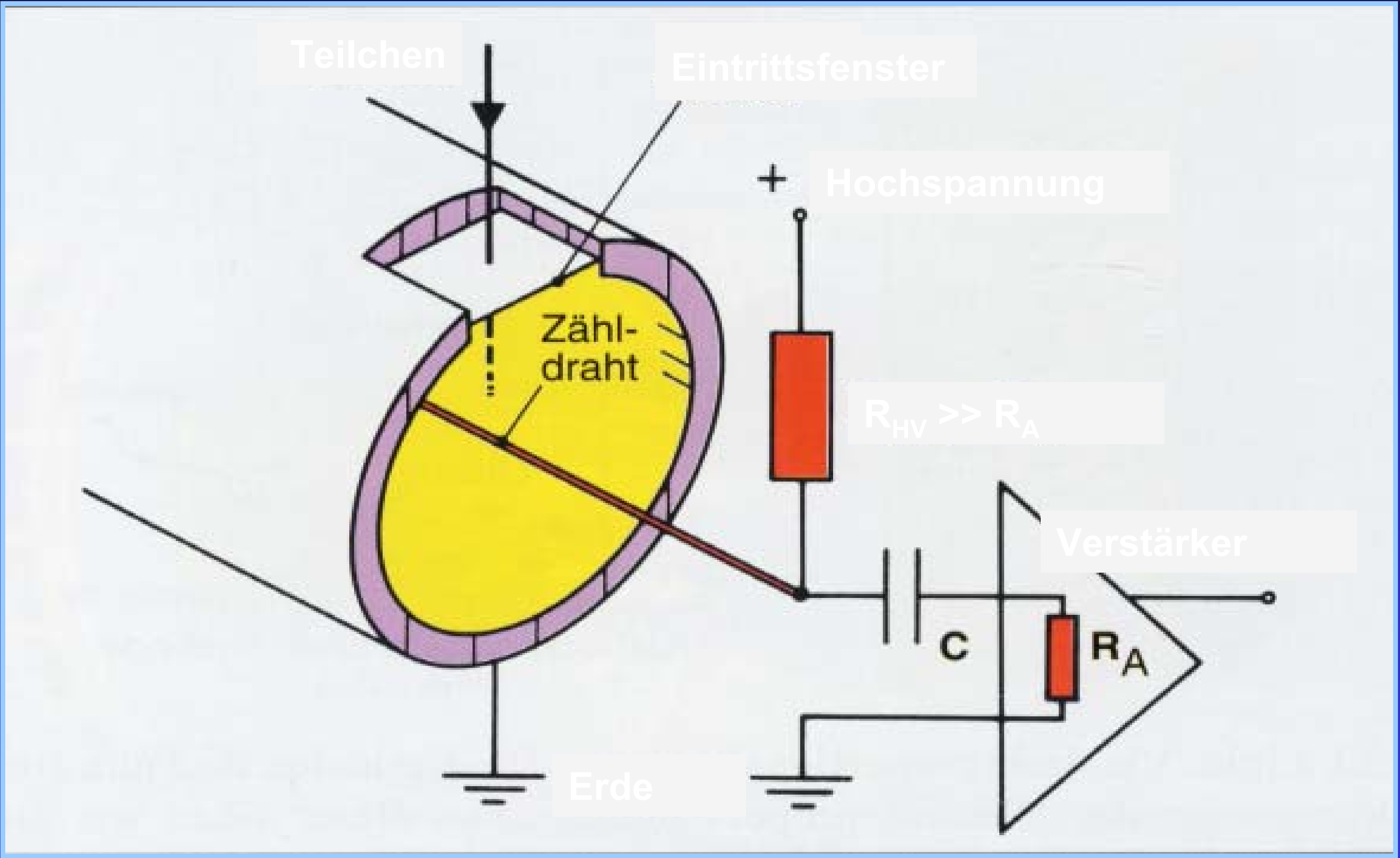
- dominant detector from ~ 1960-1975
- container with liquid in boiling retardation
- particles moving through the detector ionize the liquid molecules, which are seeds for vapor bubbles along the particle‘s track
- photographic pictures are taken of the visible tracks





Particle detectors

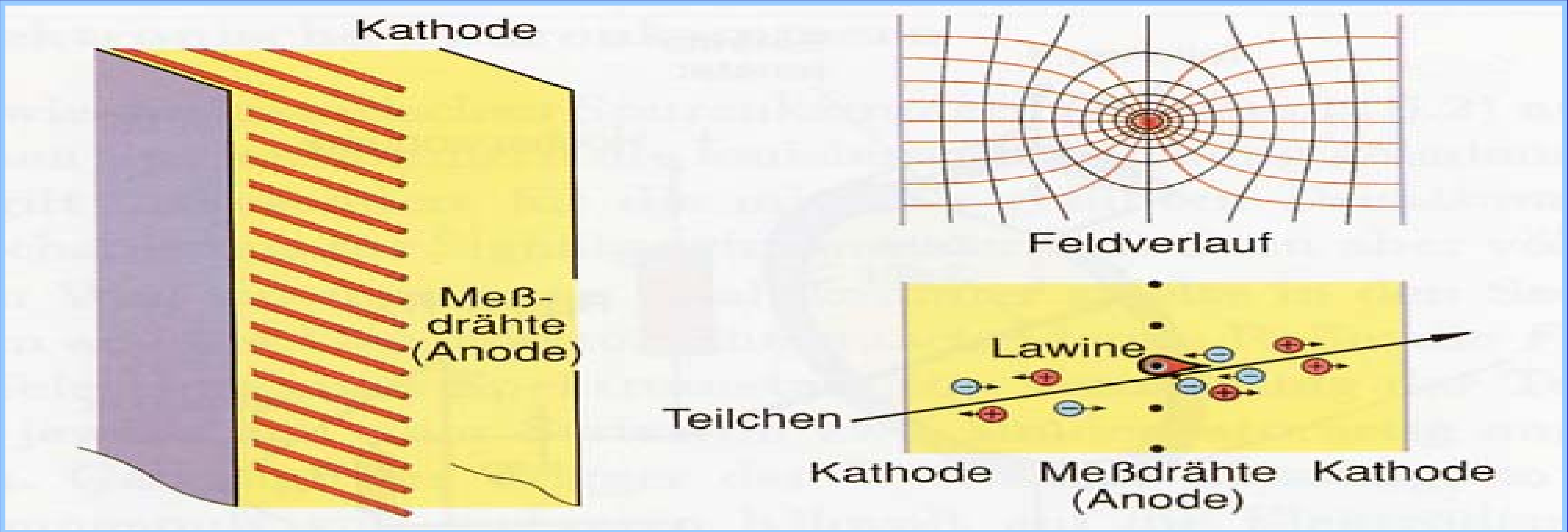
wire counters



Particle detectors

multi-wire proportional chamber:

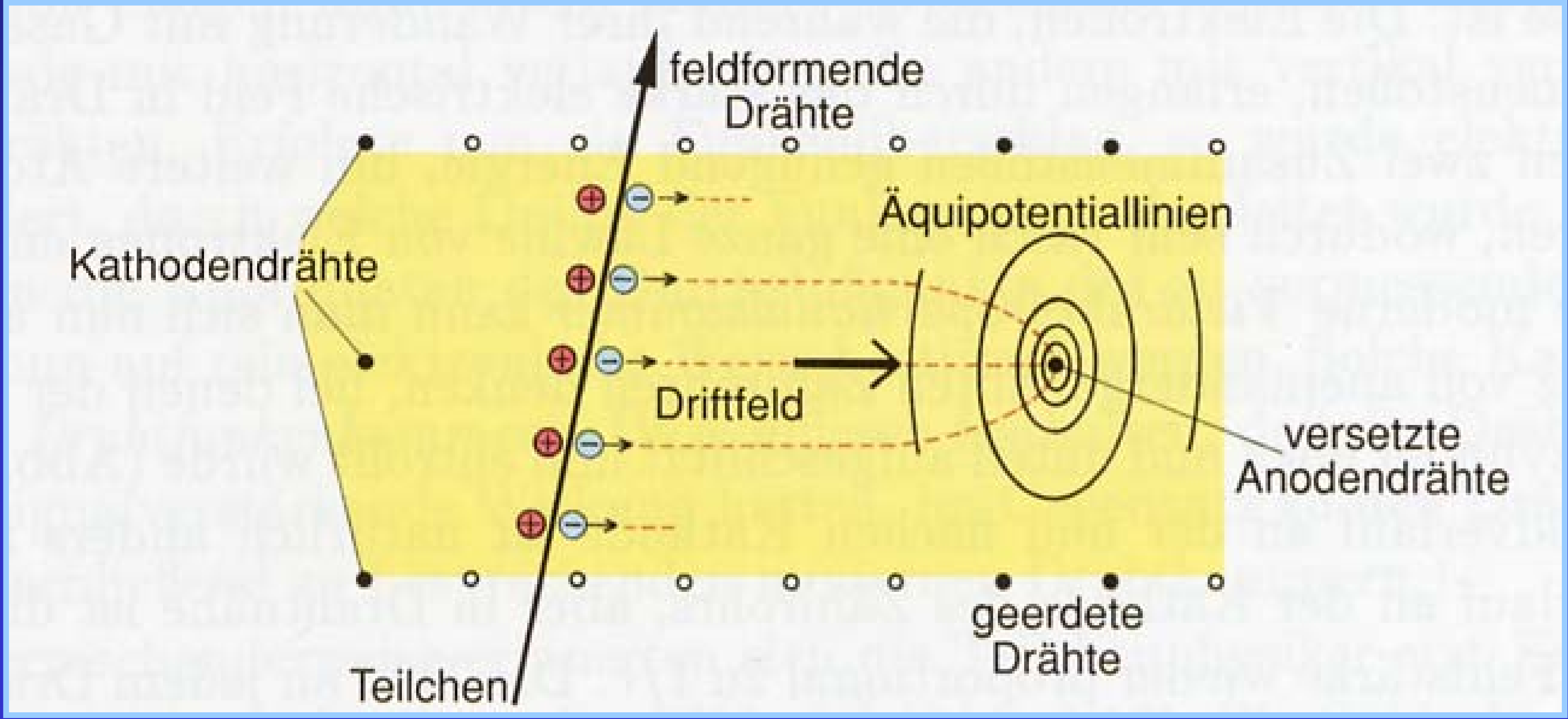
- same principle as simple counter: passing particles produces free electrons per ionization
- electrons travel to counting wire, high field strength near wire result in avalanche-effect → large number of electrons set free
- ions drift to cathode and give an electric signal



Particle detectors

drift chamber:

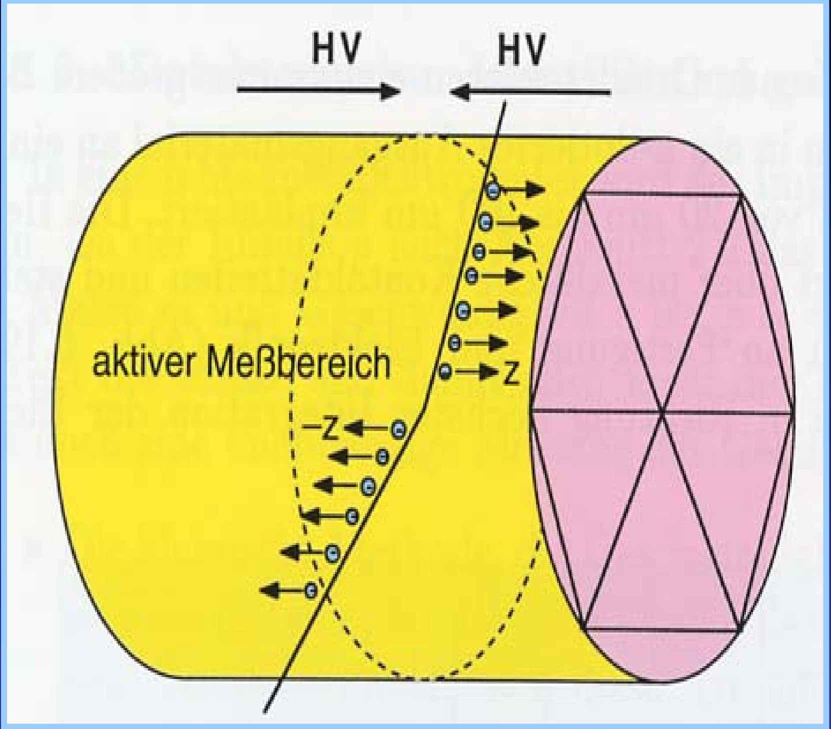
- distance between wires increased to several cm
- strong quasi-homogeneous electrical drift field
- measured drift time gives distance of particle to nearest wire



Particle detectors

time projection chamber:

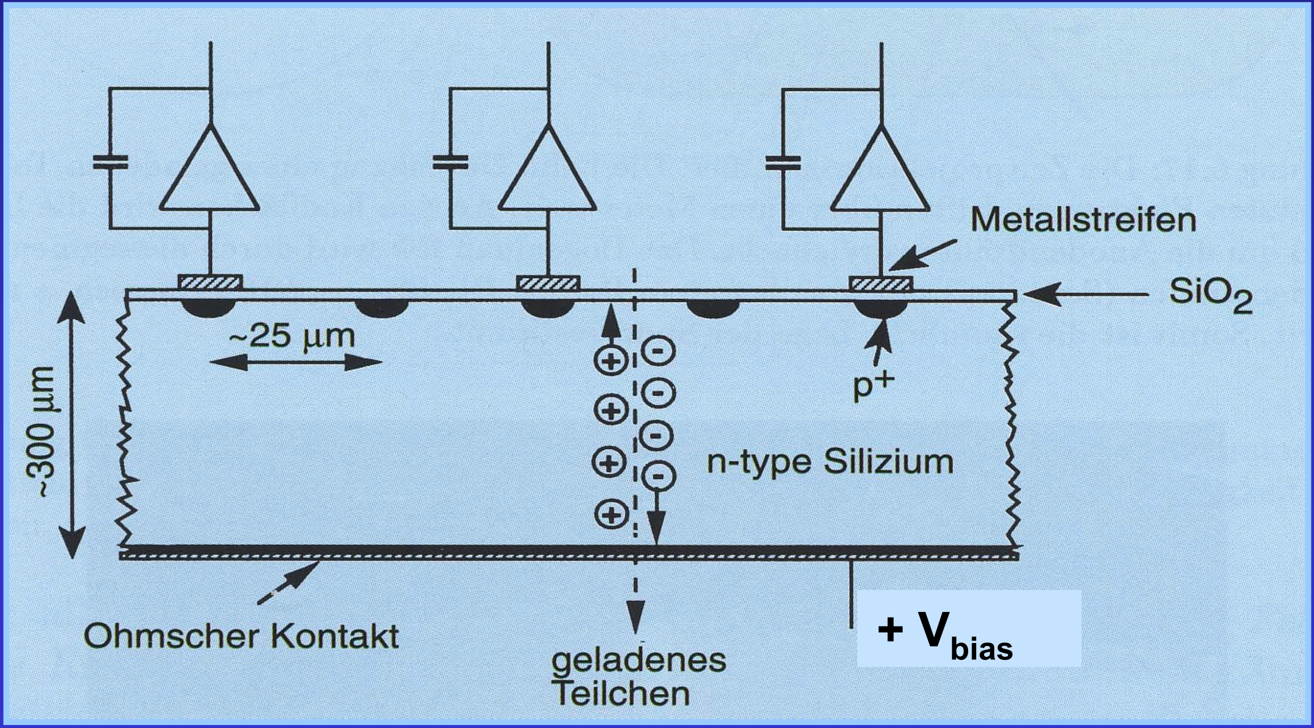
- drift field in a large 3d space
- z-coordinate measured by drift time
- x,y-coordinates measured at endcaps with complex counting wire structure



Particle detectors

semi-conductor detectors:

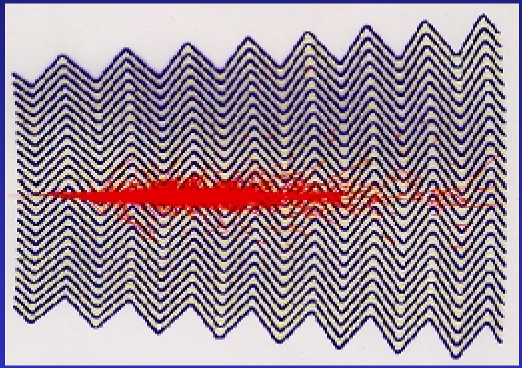
- diodes in reverse-biasing
- thermical electrons removed by electrical field
- passing particles produce signal
- pixel structures, resolutions up to 1µm reached

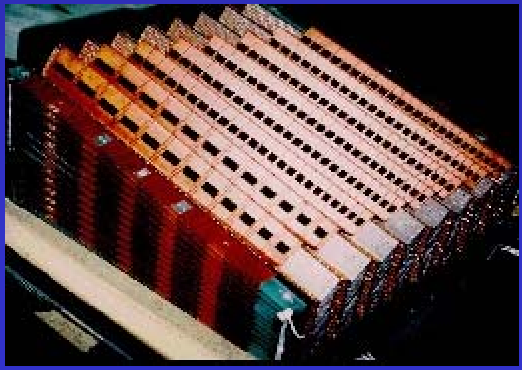


Particle detectors

calorimeters:

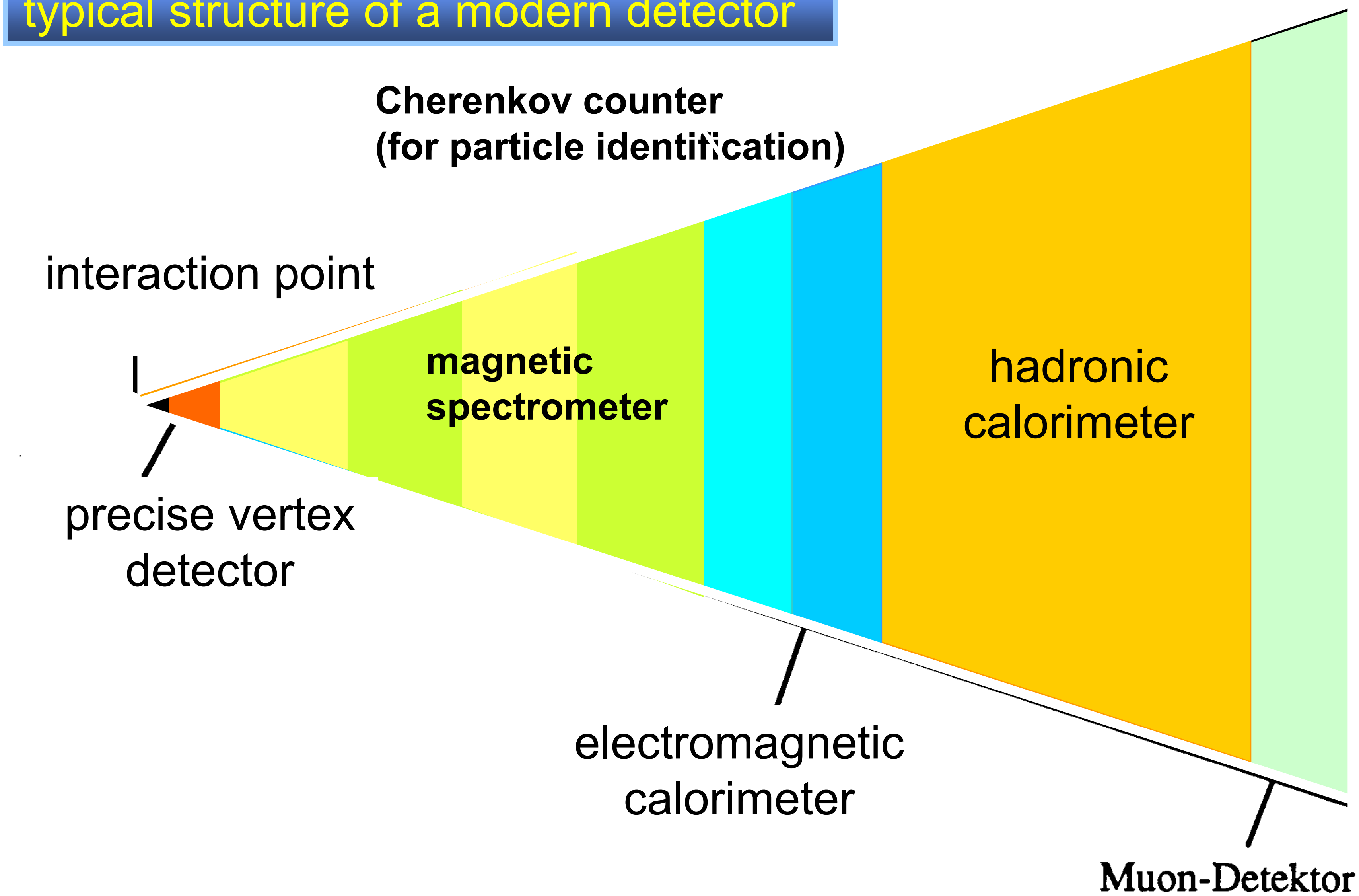
- aim: measure energy of particles by absorbing them
- basic physical process: particles produce a shower of low-energetic particles in calorimeter material
- electro-magnetic calorimeters use high-Z material (elm. interaction goes with Z^2); they only absorb electrons and photons totally, other particles leave only partial energy
- hadronic calorimeters use dense material (like lead glass); they absorb strongly-interacting particles like protons or pions, but still can be passed by muons





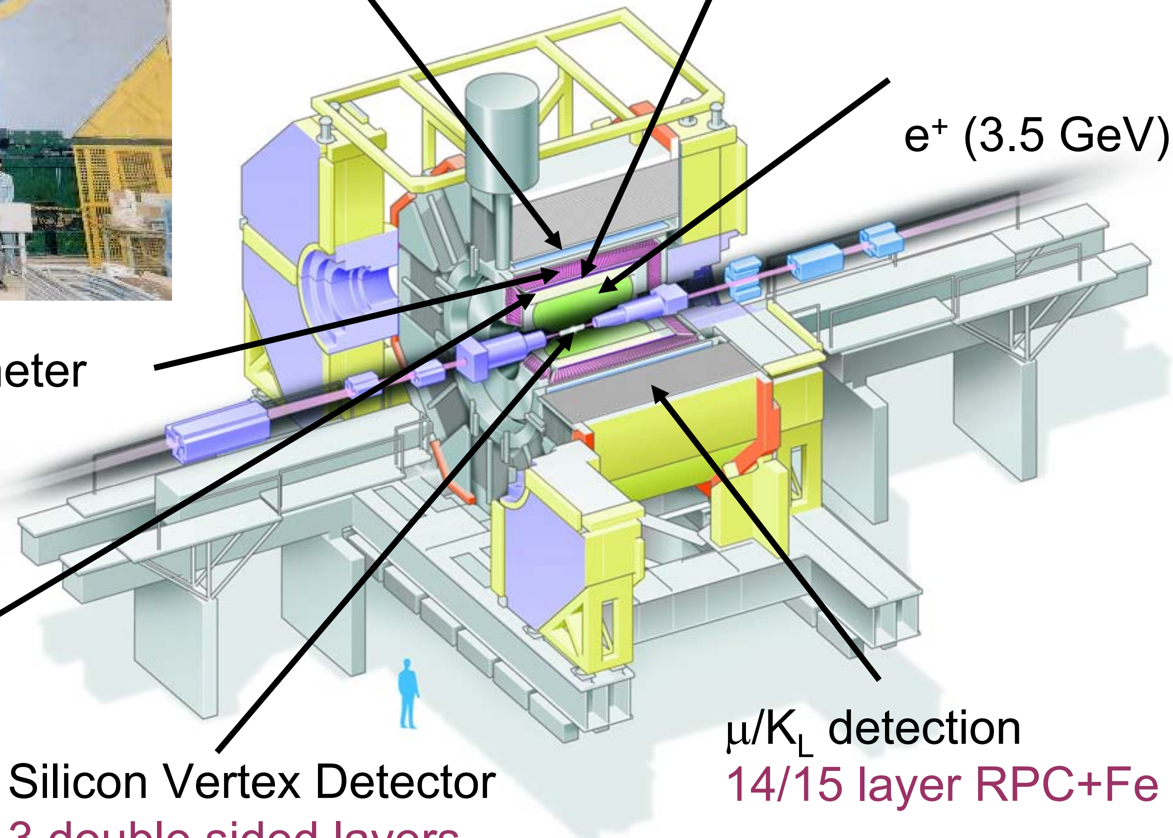
Particle detectors

typical structure of a modern detector



Particle detectors

Example: the BELLE detector



Laboratories world-wide

Overview of current world-wide experiments

experiment	accelerator	lab	research topics
CDF, D0	TEVATRON	FNAL **(Chicago/USA)**	top physics, higgs-search
STAR	RHIC	BNL **(New York/USA)**	quark-gluon-plasma
BABAR	PEP II	SLAC **(California/ USA)**	CP violation
BELLE	KEK B	KEK **(Japan)**	CP violation
H1, ZEUS	HERA	DESY **(Germany)**	QCD
CMS, ATLAS, ALICE, LHCb	LHC	CERN **(Switzerland)**	higgs search, new physics

What did we learn from the experiments of the past?

→ Unit III (tomorrow): Symmetries
→ Unit IV (WED): The Standard Model

- END of Unit II -

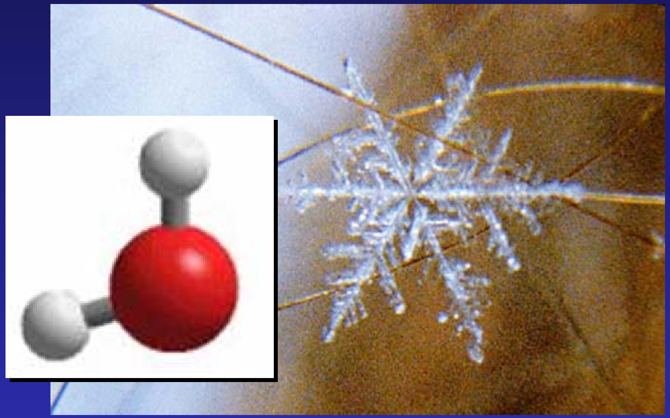
Introduction to Particle Physics

Overview

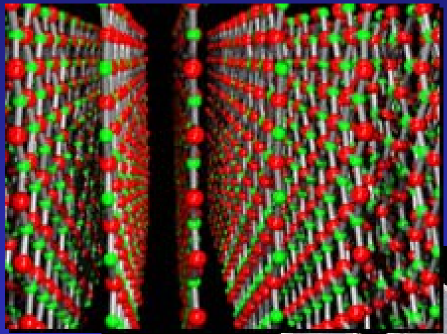
Unit I:	The Particle Zoo
Unit II:	Accelerators & Detectors
Unit III:	Symmetries
Unit IV:	The Standard Model (& beyond)
Unit V:	CP-Violation in B-Decays (BELLE)

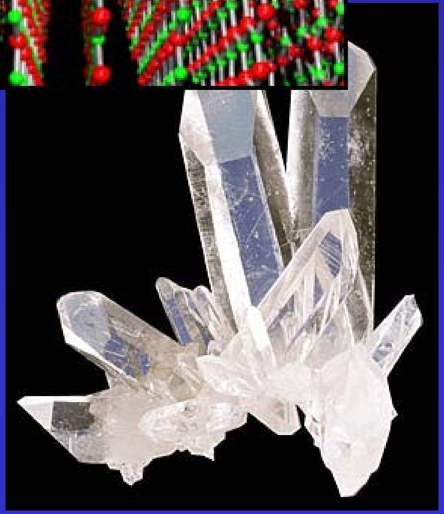
Symmetries – where do we find them?

→ everywhere in nature:



• snow flakes exhibit a 6-fold symmetry





• crystals build lattices

→ symmetries of the microcosm are also visible in the macrocosm!

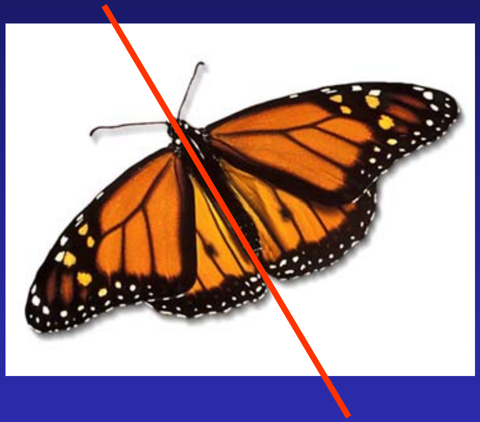
How do symmetries look like in theory?

- symmetries are described by symmetry transformations:

Example 1: Butterfly

<u>symmetry transformation S_1</u>:

mirror all points at a line!



formally: W=„original picture“ → W‘=„mirrored picture“

apply symmetry in operator notation: $S_1W=W'$

symmetry is given <u>if and only if</u> $S_1W=W$!

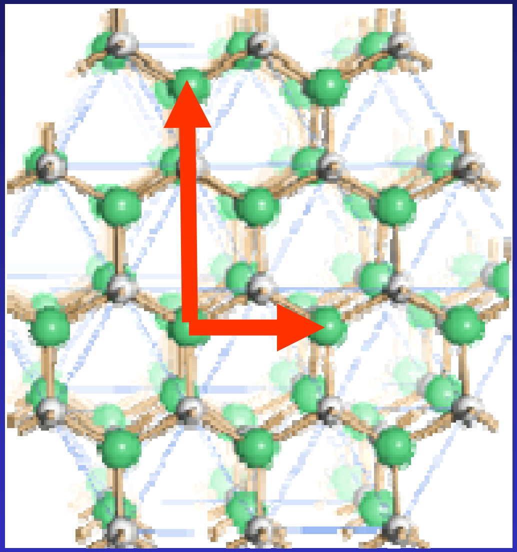
How do symmetries look like in theory?

- symmetries are described by symmetry transformations:

Example 2: crystal lattice

symmetry transformation S_2:

move all points by same vector!



formally: W=„original picture“ → W‘=„moved picture“

apply symmetry in operator notation: $S_2W=W'$

symmetry is given if and only if $S_2W=W$!

Which types of symmetries do we encounter in particle physics?

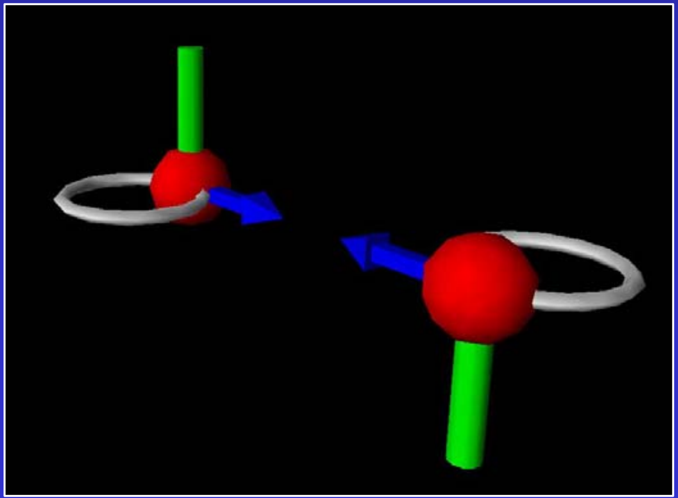
➔ discrete symmetry transformations:

parity transformation P

- to mirror at a plane, e.g. a mirror, is easy to understand, but depends on the (arbitrary) position and orientation of the plane.
- more general definition: mirror at origin (space inversion, parity transformation):

$$PW(x,y,z,t) := W(-x,-y,-z,t)$$

- parity transformations correspond to a rotation followed by a mirroring at a plane



Which types of symmetries do we encounter in particle physics?

→ discrete symmetry transformations:

Reversion of time's arrow: time inversion T

- corresponds to a movie played backwards
- in case of a movie (= everday physics), this is spotted at once (i.e. there is no symmetry)
- however, the laws of mechanics are time-symmetric! (example: billiard)
- definition:

$$TW(x,y,z,t) := W(x,y,z,-t)$$

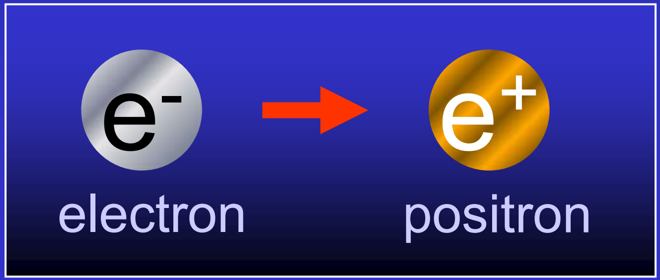
Which types of symmetries do we encounter in particle physics?

→ discrete symmetry transformations:

anti-matter : charge conjugation C

- for every known particle, there is also a anti-partner
- anti particles are identical to their partners with respect to some properties (e.g. mass), and opposite w.r.t. others (e.g. charge)
- charge conjugation exchanges all particles with their anti partners (and vice versa)
- **definition:**

$$C W(x,y,z,t) := \overline{W}(x,y,z,t)$$



Which types of symmetries do we encounter in particle physics?

→ continuous symmetry transformations:

(symmetry transformations that can be performed in arbitrarily small steps)

- **time**: physics(today) → physics(tomorrow)

  more accurate: **shift** by a time-step Δt:

  $$e^{\Delta t\, \partial/\partial t}\, W(x,y,z,t) = W(x,y,z,t+\Delta t)$$

- **space**: physics(here) → physics(there)

  more accurate: **displacement** in space by a vector $\Delta r=(\Delta x, \Delta y, \Delta z)$:

  $$e^{\Delta r \nabla}\, W(x,y,z,t) = W(x+\Delta x,y+\Delta y,z+\Delta z,t)$$

Which types of symmetries do we encounter in particle physics?

→ continuous symmetry transformations:

(symmetry transformations that can be performed in arbitrarily small steps)

- **orientation**: physics(north) → physics(west)

more accurate: rotation around an arbitrary axis in space:

$$D\Psi(x,y,z,t) = \Psi(x',y',z',t)$$

Which types of symmetries do we encounter in particle physics?

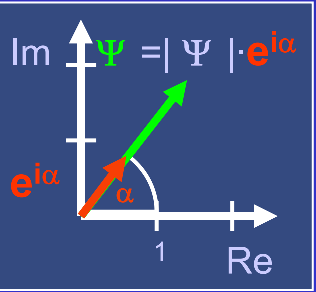
→ continuous symmetry transformations:

(symmetry transformations that can be performed in arbitrarily small steps)

- **U(1) transformation:**
  - does not affect the outer coordinates x,y,z,t, but inner properties of particles
  - U(1) is a transformation, which rotates the phase of a particle field (denoted as Ψ) by an angle α:

$$U(1)\Psi(x,y,z,t)=e^{i\alpha}\,\Psi(x,y,z,t)$$

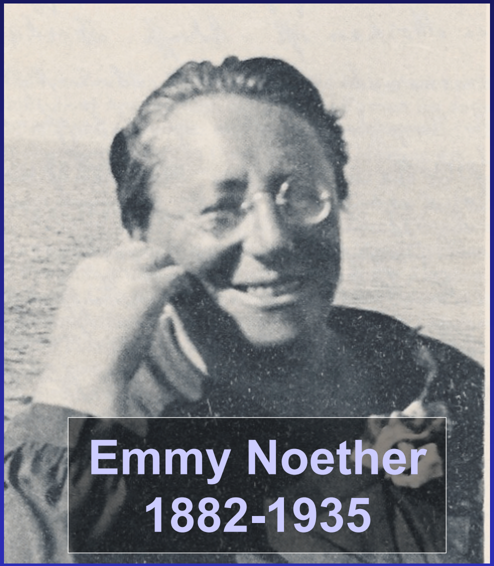
insertion: particles are represented by fields in quantum field theory. At each point in space and time, the field Ψ can have a certain complex phase.



The fundamental importance of symmetries

➔ Noether❻s theorem:

to each symmetry of a field theory corresponds a certain conserved quantity, i.e. a conservation law



Emmy Noether
1882-1935

that means: if a field theory remains unchanged under a certain symmetry transformation S, then there is a mathematical procedure to calculate a property of the field which does not change with time, whatever complicated processes are involved.

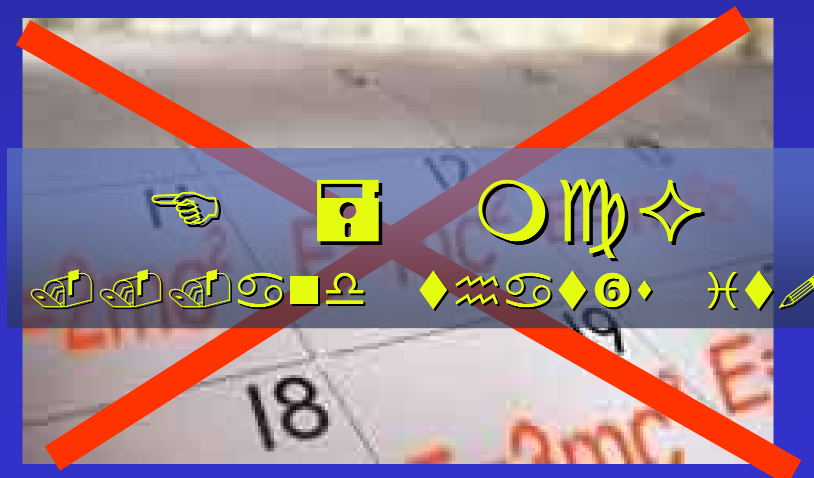
The fundamental importance of symmetries

→ applications of Noether❻s theorem:

also tomorrow the sun will rise → **the conservation of energy**

- the laws of physics do not change with time
- **more accurate**: the corresponding field theory is invariant under time shifts:

$$e^{\Delta t\, \partial/\partial t}\, W(x,y,z,t) = W(x,y,z,t+\Delta t) = W(x,y,z,t)$$



From **Noether's theorem** follows the conservation of a well-known property: **energy**!

Insertion (just to be clear):

→ we are talking about properties of the underlying theory, not a certain physics scenario

Example: chess

- there is virtually an infinite number of ways a game of chess can develop
- a game tomorrow can be completely different from that today

but:

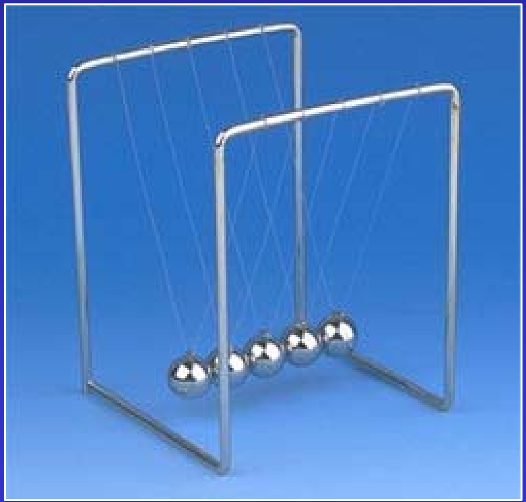
- the rules of chess remain the same, they are invariant under time shifts!

The fundamental importance of symmetries

➔ applications of Noether❻s theorem:

it's the same everywhere → the conservation of momentum

- the laws of physics do not depend on where you are
- more accurate: the corresponding field theory is invariant under space displacements:



$e^{\Delta r \nabla} W(x,y,z,t) = W(x+\Delta x, y+\Delta y, z+\Delta z, t) = W(x,y,z,t)$

From Noether's theorem follows the conservation of another well-known property: **momentum**!

The fundamental importance of symmetries

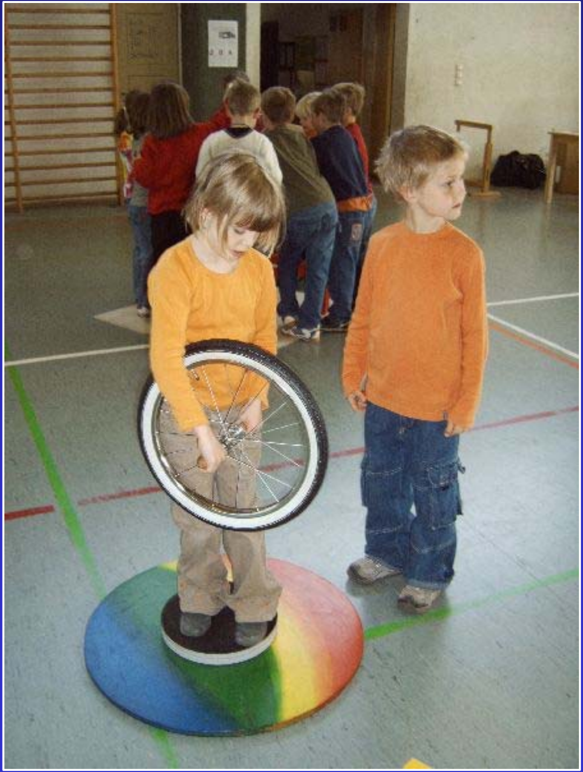
→ applications of Noether❻s theorem:

going round and round – the conservation of angular momentum

- **the laws of physics do not depend on which way you look**
- **more accurate: the corresponding field theory is invariant under rotations:**

$$DW(x,y,z,t) = W(x,y,z,t)$$

From Noether's theorem follows the conservation of yet another well-known property: angular momentum!



The fundamental importance of symmetries

➔ applications of Noether❻s theorem:

even more abstract symmetries get a meaning:

the conservation of charge

• as it turns out, <u>the field theory of electro-dynamics is invariant under a global* U(1) transformation:</u>

$U(1)\Psi(x,y,z,t)=e^{i\alpha}\,\Psi(x,y,z,t) \;\rightarrow\; W'=W$

From Noether's theorem follows the conservation of charge!

* global means affecting all space-points x,y,z,t the same

Overview

symmetries and conservation laws

symmetry	conservation law
time	energy
space	momentum
rotation	angular momentum
U(1) phase	charge

Are symmetries perfect?

→ the small imperfections make it more interesting...

is physics really perfectly symmetric?

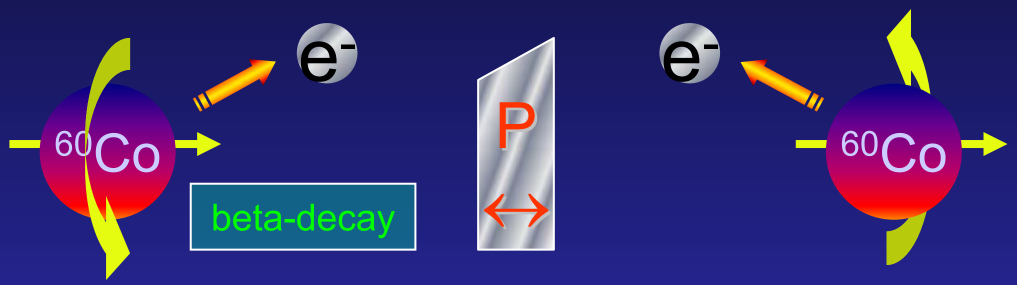
- **obviously, many things in our macroscopic world are not symmetric**
- **but is this also true for the fundamental laws of physics?**

→ Originally it seemed that nature does not only exhibit the previously discussed continuous symmetries, but the discrete symmetries as well:

- **P (parity = mirror symmetry)**
- **T (time inversion)**
- **C (charge conjugation)**

Are symmetries perfect?

→ the Wu experiment



Chien-Shiung Wu
1912-1997

- originally, all experiments indicated that the microcosmic world is perfectly mirror-symmetric
- 1956 Tsung-Dao Lee and Chen Ning Yang postulated a violation of parity for the weak interaction
- in the same year, Chien-Shiung Wu demonstrated the violation experimentally

Tsung-Dao Lee &
Chen Ning Yang

→ nature is <u>not</u> mirror-symmetric,
P-symmetry (parity) is <u>violated</u>

Are symmetries perfect?

a deeper understanding of the Wu experiment

- also (undetected) **anti-neutrinos** are emitted
- anti-neutrinos have a spin that is always orientated in the direction of movement (they are „**right-handed**“)
- since a **P-transformation** changes the direction of movement, but not the spin, it produces a „**left-handed**“ anti-neutrino
- as it turns out, **a left-handed anti-neutrino does not exist in nature at all!**
- therefore, **P-symmetry** is said to be **maximally violated**

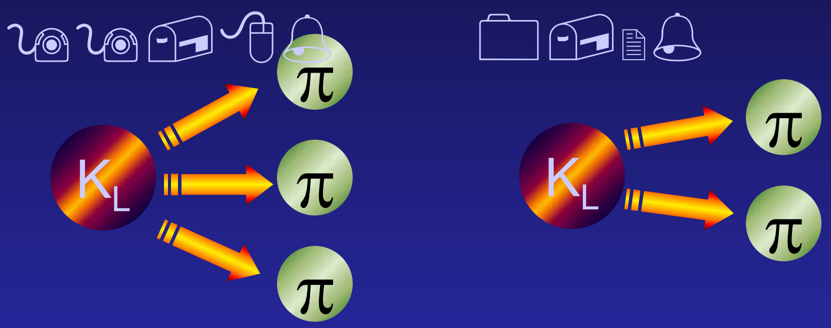
Are symmetries perfect?

P violation ⇒ but maybe a CP symmetry?

- there is **no left-handed anti-neutrino**, but there is a **left-handed neutrino** (and only a such-handed!)
- obviously, this violates **C-symmetry** (symmetrie between matter and anti-matter)
- BUT: the **combined symmetry transformation CP** (exchange matter/anti-matter plus mirroring) **works**:

Are symmetries perfect?

→ the kaon experiment of 1964



long-lived kaon decay into pions

- if there is **CP**-symmetry in nature, by **Noether's theorem** there is also a corresponding **conserved quantum number „CP"**
- one has to know that mesons like the kaon or the pion are **pseudo-scalars**, which mean they change sign under a **P**-transformation:

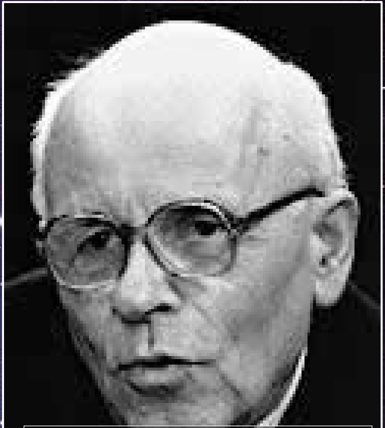
$$PK = -K, \quad P\pi = -\pi$$

- therefore, CP is conserved for the decay of the long-lived kaon into **three** pions, but not for the decay into **two**

→ CP-Symmetry is (slightly) <u>violated</u>

Are symmetries perfect?

→ implications of CP-violation in cosmology


Andrej Sacharow
1921-1989

why CP-violation is important for our existence:

- our universe consists – as far as we know – almost completely of matter
- but where is the anti-matter?
- and why haven't matter and anti-matter just annihilated?

→ possible explanation:

- at big bang, there have been large amounts of both matter and anti-matter
- almost all of them annihilated
- but smallest asymmetries in the laws of nature for matter and anti-matter left a tiny excess of matter: the matter our universe is made of!
- 1967, Andrej Sacharow gave a list of conditions for this explanation
- one of it is CP-violation

Without CP-violation, our universe would not be the one we know!

Are symmetries perfect?

→ ④last hope⑧ CPT-symmetry?

• the CPT-theorem states that under very general conditions, quantum field theories always have to exhibit CPT-symmetry
• also experimentally, no violations have been observed so far

→ CPT-Symmetry is (as far as we know today) <u>not violated</u>

• interesting side remark: as a consequence of CPT-symmetry together with CP-violation, there has to exist a violation of T-symmetry
• that means: the fundamental laws of nature are not time-symmetric, there is a special direction of time even at microscopic level
• „future IS different from the past, after all!“

Overview

discrete symmetries

symmetry	valid in the universe?
P (mirroring)	✗
C (exchange matter/anti-matter)	✗
T (time inversion)	✗
CP (combination of C and P)	✗
CPT (combination of C,P & T)	✓

How symmetries make theories

→ QED, the quantum theory of light

remember:

- physics is invariant under a U(1)-transformation of the particle field Ψ,

$$U(1)\ \Psi(x,y,z,t) = e^{i\alpha}\ \Psi(x,y,z,t)$$

- the phase α here is global, that means a synchronous phase transformation of all particles in the whole universe!

the idea:

- replace global transformation by a local one:

$$U(1)\ \Psi(x,y,z,t) = e^{i\alpha(x,y,z,t)}\ \Psi(x,y,z,t)\ ?$$

(different particles at different positions get transformed independently)

How symmetries make theories

→ QED, the quantum theory of light

consequence of a local U(1) transformation:

- **if only particles are transformed (not including their electromagnetic interaction), then the theory is not invariant under local U(1) transformations!**

- **however, if electromagnetic interaction is included, then the theory**

  is locally U(1) symmetric!

- **this works only, because the electromagnetic interaction has just the right form**

→ coincidence or deeper truth?

How symmetries make theories
→ QED, the quantum theory of light

the modern view:

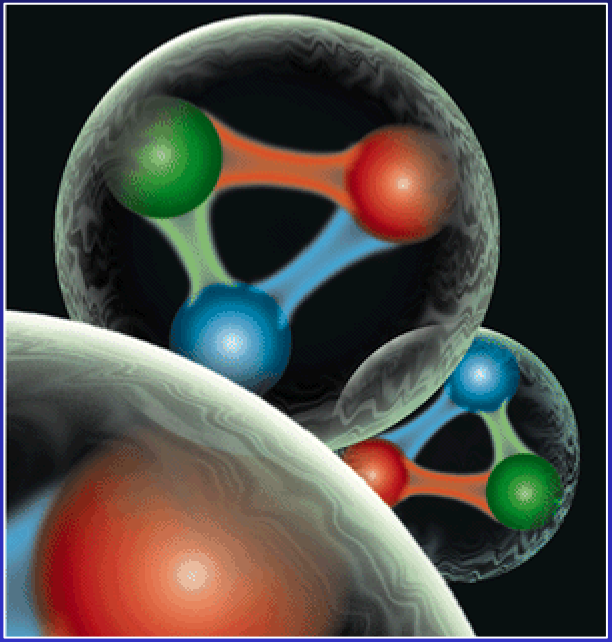
- for a given global symmetry, it is postulated that it is also valid locally
- from this, one gets automatically an interaction connected with this symmetry
- in addition, one gets additional particles (force carriers, for U(1) it is the photon), which mediate the interaction

each local symmetry produces an interaction plus new particles which mediate it

How symmetries make theories
→ Quantum-Chromo-Dynamics (QCD) the theory of the strong force

- experiments showed that protons (and neutrons) have an **inner structure**
- the observed symmetries suggested the postulation of the existence of 3 **quarks** inside the nucleon.
- quarks have an additional property, called **color**

there are three color states: red, green, blue



How symmetries make theories
→ Quantum-Chromo-Dynamics (QCD) the theory of the strong force

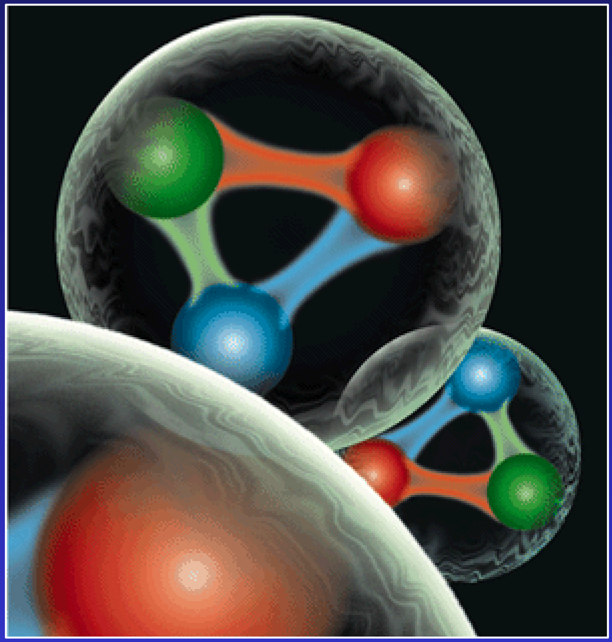
- **idea: there is a symmetry between different color states, i.e. they can be arbitrarily re-mixed without changing the theory:**

„new colors“

$$q = A_{rr}\, q + A_{rg}\, q + A_{rb}\, q$$

$$q = A_{gr}\, q + A_{gg}\, q + A_{gb}\, q$$

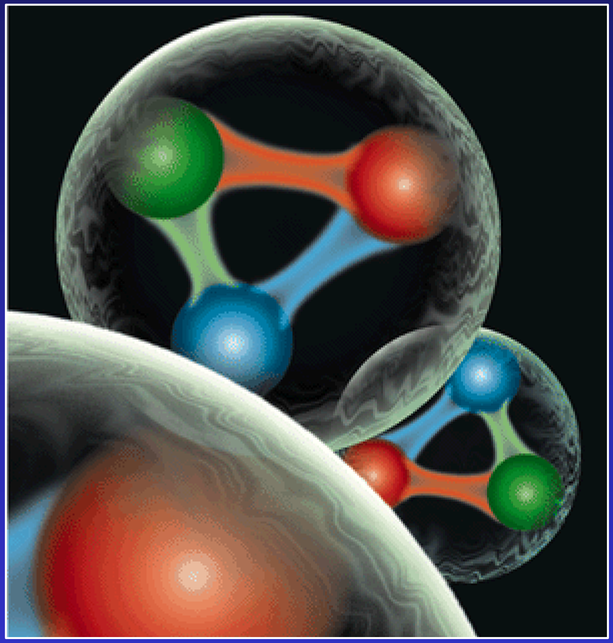
$$q = A_{br}\, q + A_{bg}\, q + A_{bb}\, q$$



- **mathematically, this corresponds to a 3x3 matrix A, and the symmetry group is known as SU(3)**

How symmetries make theories
→ Quantum-Chromo-Dynamics (QCD) the theory of the strong force

- by postulating a local SU(3) symmetry, one automatically gets a new kind of interaction between the quarks
- it is known as strong force, the corresponding force carriers are called gluons
- it is responsible for the binding of mesons and baryons
- and as well for the stability of nuclei



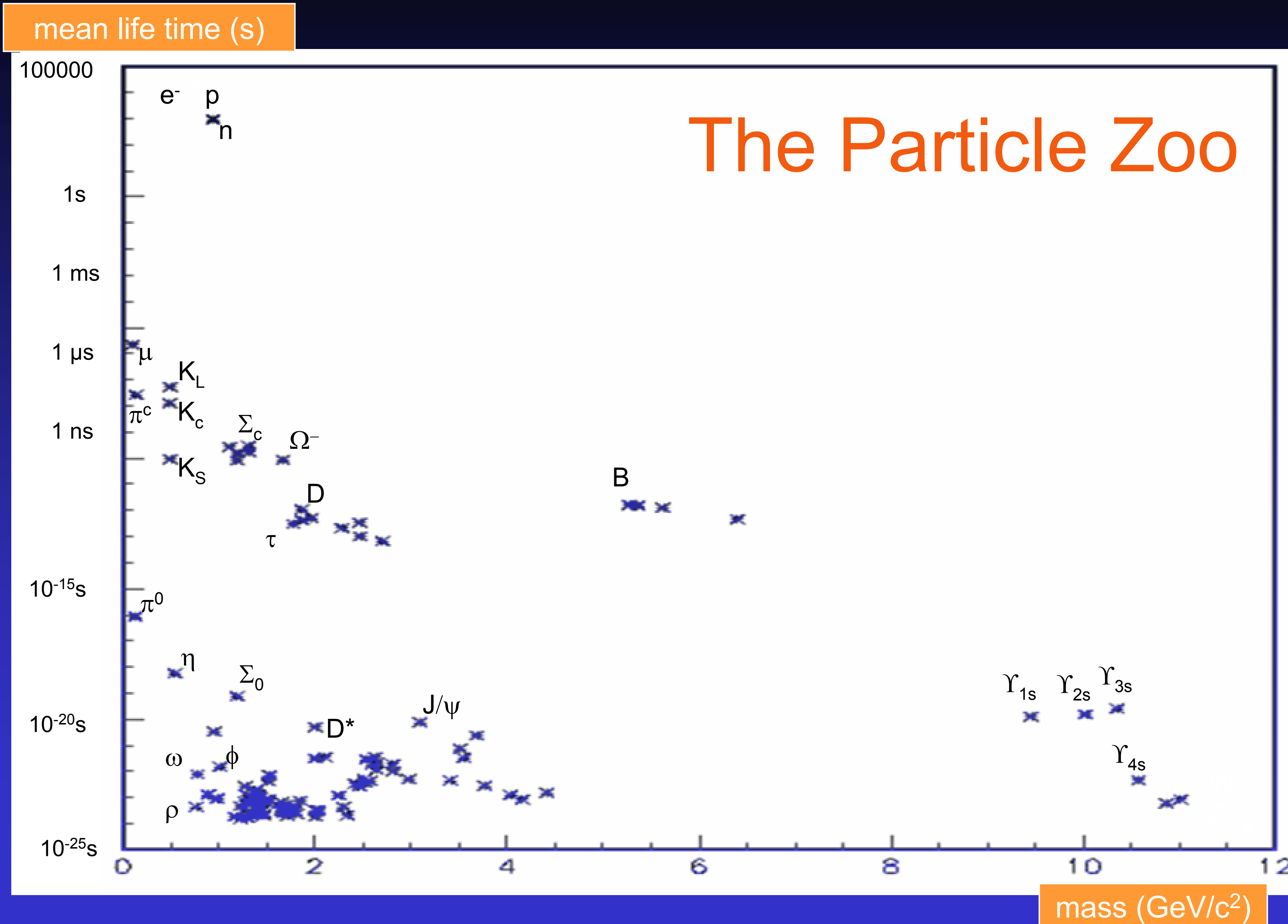
the color symmetry of quarks enables the existence of atoms!

next:

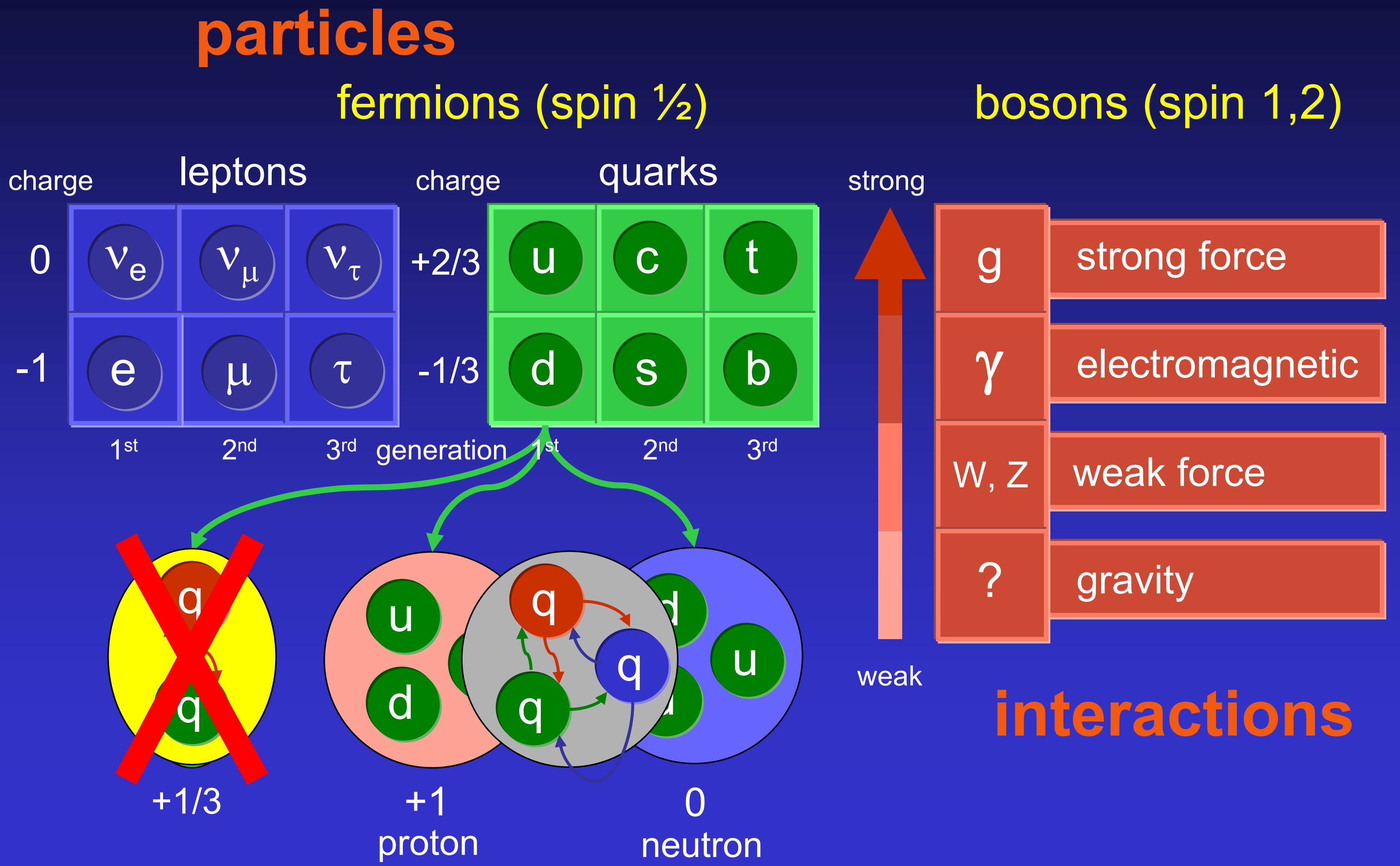
→ **putting everything together:
the standard model**

- break -

The Particle Zoo



The Standard Model - Overview



The Standard Model - Overview

anti particles

fermions (spin ½)

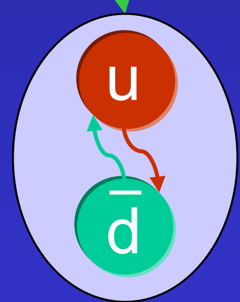
leptons

charge	1st	2nd	3rd
0	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
+1	$\bar{e}$	$\bar{\mu}$	$\bar{\tau}$

quarks

charge	1st	2nd	3rd
-2/3	$\bar{u}$	$\bar{c}$	$\bar{t}$
+1/3	$\bar{d}$	$\bar{s}$	$\bar{b}$

generation



+1
pion (π)

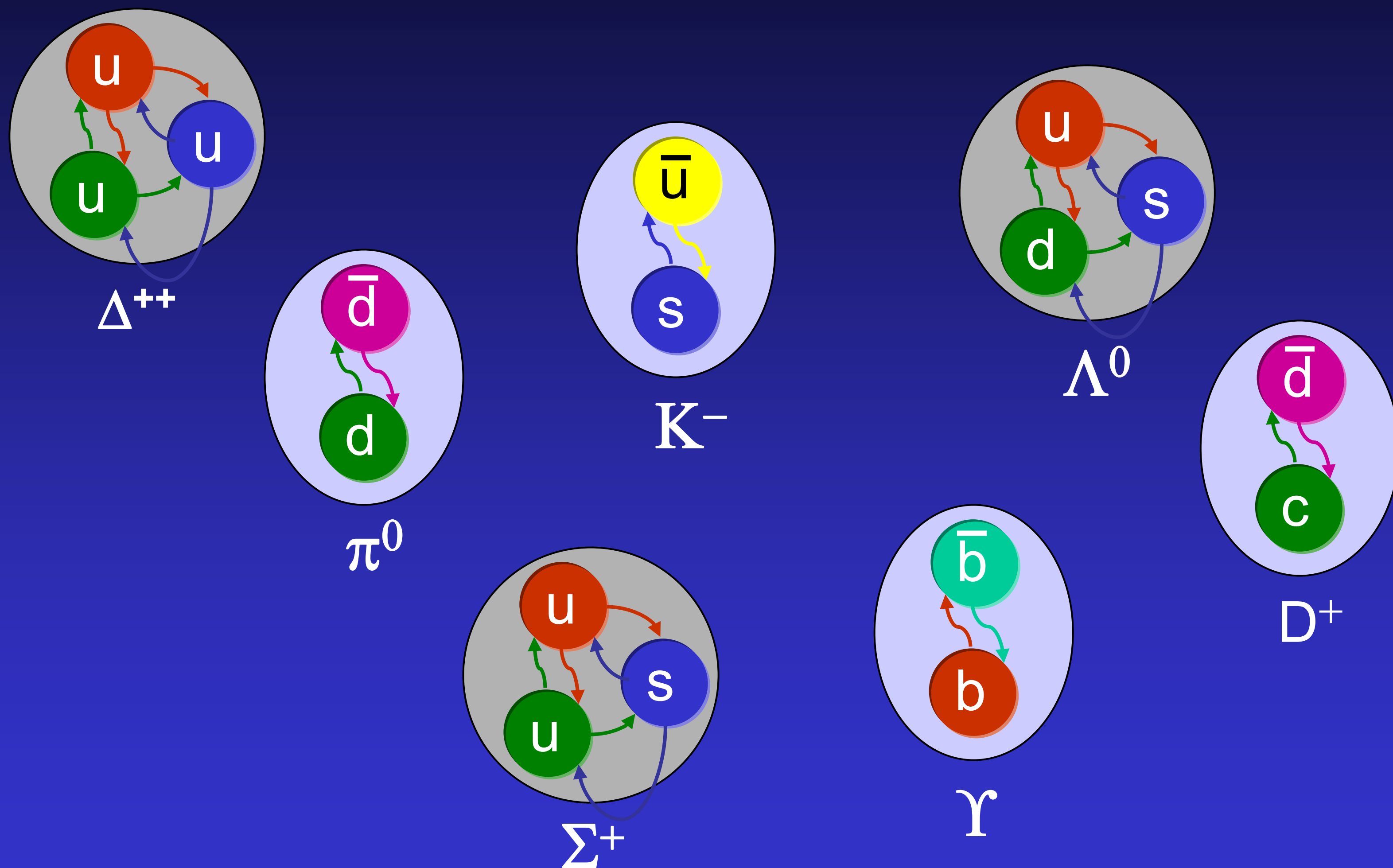
bosons (spin 1,2)

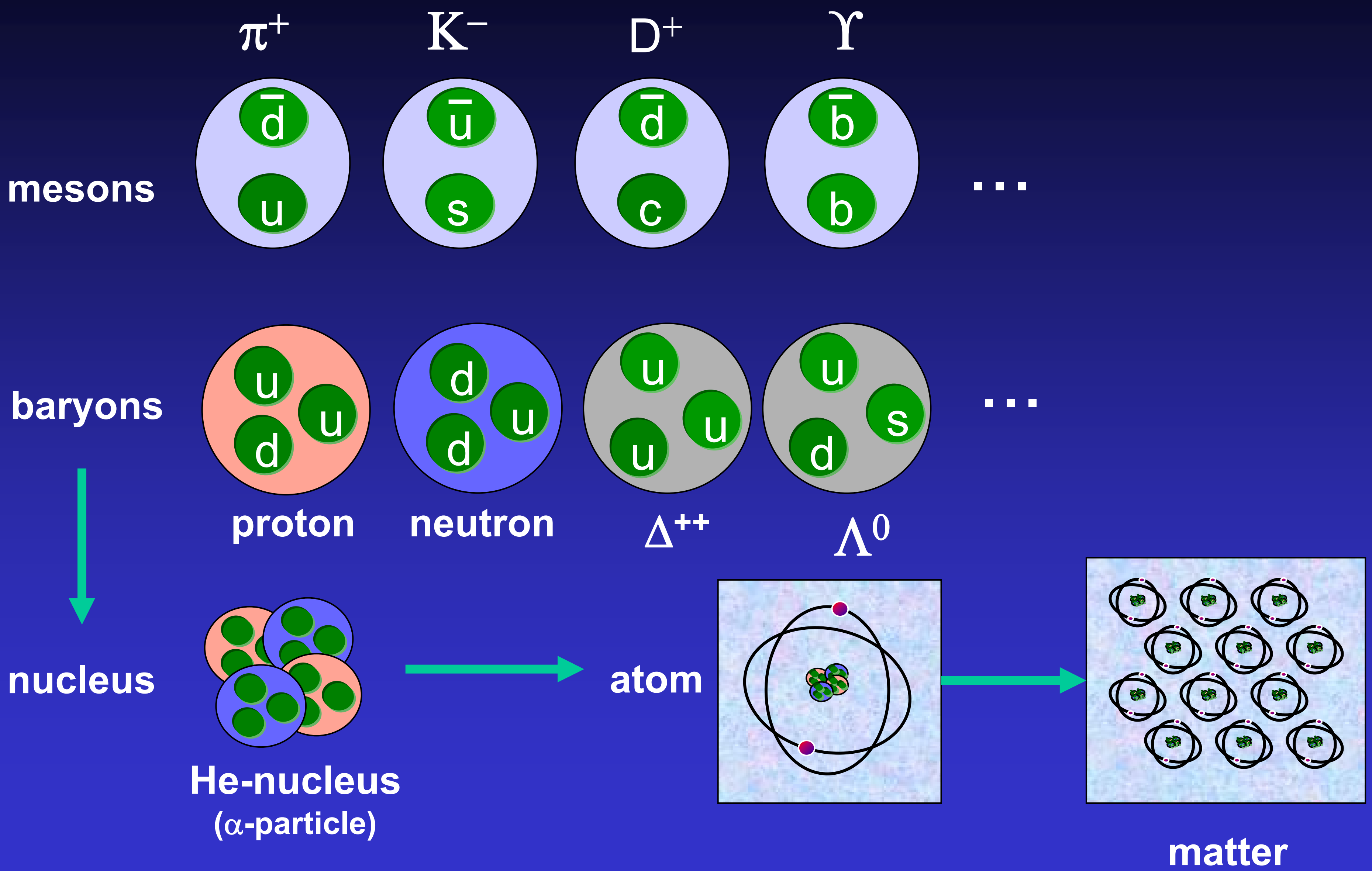
strong

g	strong force
γ	electromagnetic
W, Z	weak force
?	gravity

weak

interactions


u
u
u
Δ^{++}
$\bar{d}$
d
π^0
$\bar{u}$
s
K^-
u
s
d
Λ^0
$\bar{d}$
c
D^+
u
s
u
Σ^+
$\bar{b}$
b
Υ



π^+
K^-
D^+
Υ
mesons
$\bar{d}$ u
$\bar{u}$ s
$\bar{d}$ c
$\bar{b}$ b
...
baryons
u u d
d d u
u u u
u s d
...
proton
neutron
Δ^{++}
Λ^0
nucleus
He-nucleus
(α-particle)
atom
matter

How symmetries make theories
→ sketch of electro-weak interaction

fermions (spin ½)

charge	leptons			charge	quarks		
0	ν_e	ν_μ	ν_τ	+2/3	u	c	t
-1	e	μ	τ	-1/3	d	s	b
	1[st]	2[nd]	3[rd]	generation	1[st]	2[nd]	3[rd]

$$\nu_e = A_{uu}\,\nu_e + A_{ud}\,e$$
$$e = A_{du}\,\nu_e + A_{dd}\,e$$

$$u = A_{uu}\,u + A_{ud}\,d$$
$$d = A_{du}\,u + A_{dd}\,d$$

- postulating a **local SU(2) symmetry between up- and down-type** particles produce **a new kind of interaction** for leptons and quarks
- however, since **only left-handed neutrinos exist**, this symmetry can only involve left-handed electrons
- for **right-handed particles, a separate U(1)-symmetry** is postulated
- together they form the **electro-weak theory** of the standard model

Overview

Symmetries and Interactions

symmetry	interaction
U(1) (symmetry of right-handed leptons and quarks)	electromagnetic } electro-weak
SU(2) (symmetry of left-handed up- and down-type leptons and quarks)	weak } electro-weak
SU(3) (symmetry of quarks)	strong
? (is it a symmetry of space-time geometry itself, or something qualitatively different?)	(quantum-) gravity

symmetry breaking

example: chess

- the rules of chess are in principle **absolutey symmetric for both players**
- i.e. the rules how the pieces move are the same for black and white

but:

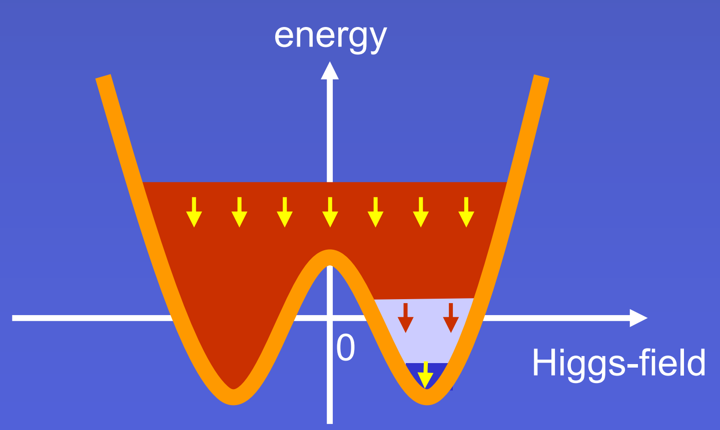
- **symmetry is broken** at the **beginning**, due to the initial setup of the pieces
- therefore, e.g. a bishop never can change the color of the field it is standing on

symmetry breaking

➔ the origin of mass

In the standard model, the particle‘s masses are an effect of symmetry breaking:

- **originally, all particles are massless**
- **but there is an additional interaction with the so-called Higgs-field**
- **if there were no Higgs-field, the interaction would have no effect**
- **however, due to a spontaneous symmetry breaking, the whole universe is filled with a non-zero Higgs-field**
- **the interaction with this omni-present field produces what we know as mass of particles**



hot universe (shortly after big bang) — **particles are massless**

cold universe (condensed into an asymmetric state) — **particles get a mass**

spontaneous symmetry breaking

symmetry breaking

→ the search for the higgs

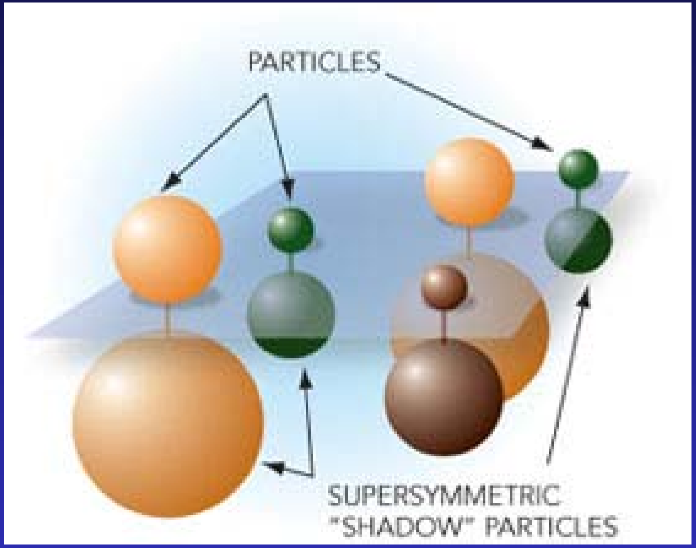
- the existence of the Higgs-field is up to today not experimentally confirmed!
- a theory of a omni-present, static field, whose only effect is giving particles their mass can not be falsified by principle
- however, a consistent theory also predicts excitations of the Higgs-field: Higgs particles
- the interaction of these Higgs particles with ordinary particles (and its strength) is completely determined by theory

→ the necessary energy and luminosity for the hunt for the higgs will be provided by the LHC (Large Hardon Collider) at CERN

the result of the search for the higgs will be one of the most important scientific results of the next years!

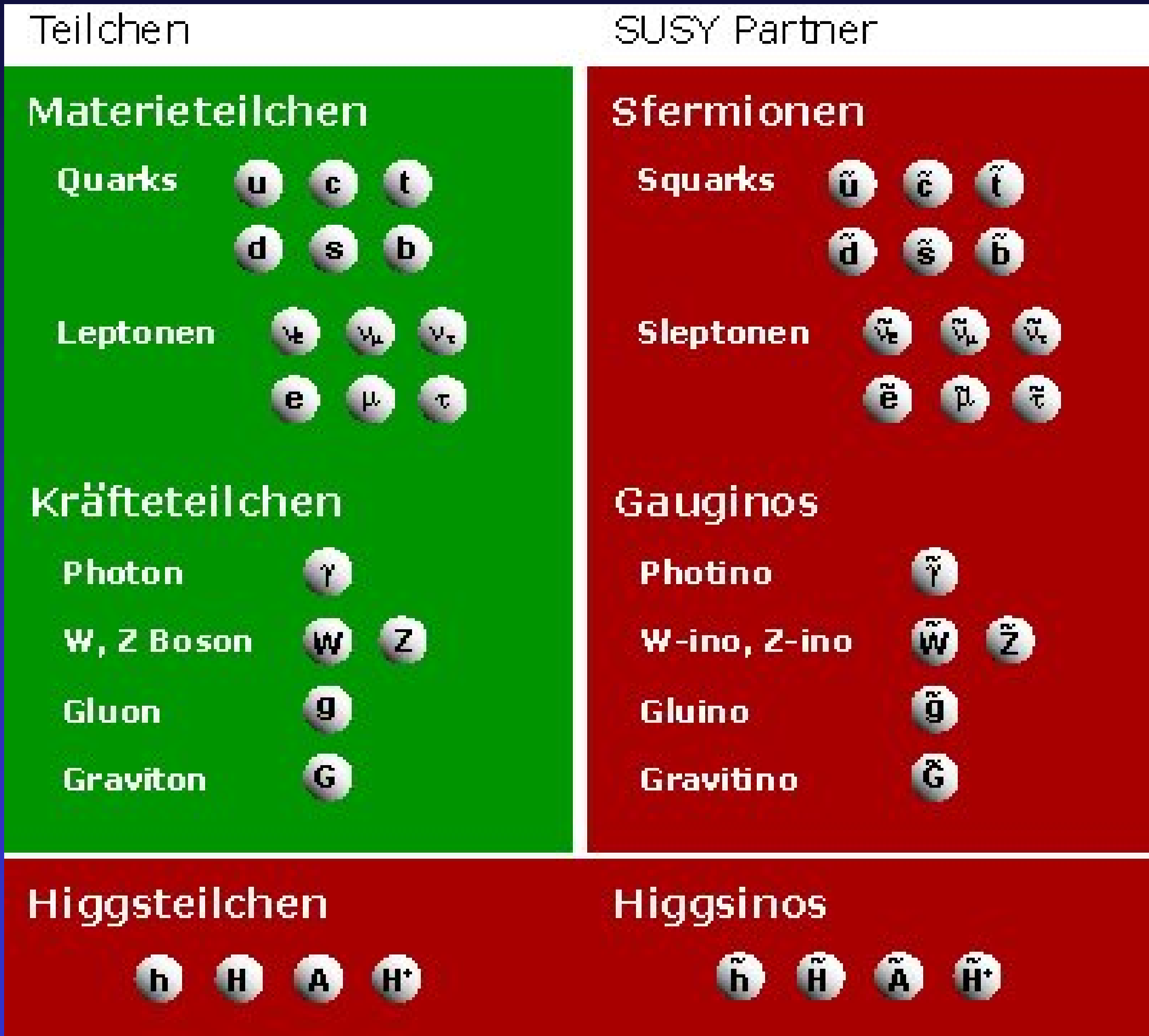
Beyond the Standard Model: Super-Symmetry (SUSY)

→ the idea:



- SUSY is a symmetry between fermions and bosons
- for that it is necessary to double the number of particles:
  - each fermion gets a super-symmetric, bosonic <u>s</u>fermion partner, e.g. top → stop
  - each boson gets a super-symmetric, fermionic bos<u>ino</u> partner, e.g. gluon → gluino

Super-Symmetry (SUSY)



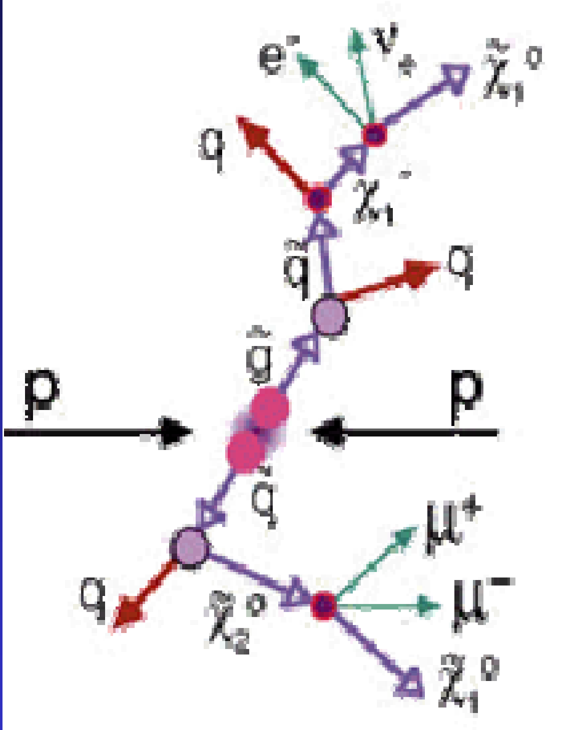
- the green region shows particles already known

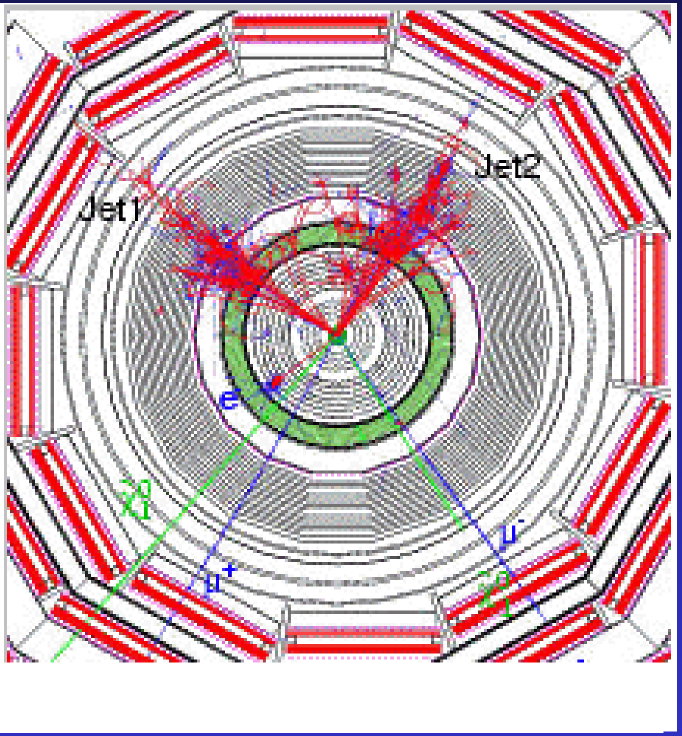
- the red region shows newly postulated particles, which have not been found in experiment yet

Super-Symmetry (SUSY)

→ in experiment:

SUSY particles could be discovered by spectacular cascade decays





The search for super-symmetric particles is one of the great challenges of today and future experiments at the Tevatron (USA), the LHC (CERN) and in the more distant future also the planned linear collider

About CP-Violation & BELLE, the experiment I am working in:

→ **Unit V (FRI): CP-Violation in B decays**

- END of Unit IV -

Introduction to Particle Physics

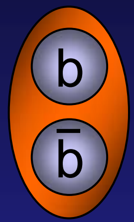
Overview

Unit I: The Particle Zoo
Unit II: Accelerators & Detectors
Unit III: Symmetries
Unit IV: The Standard Model (& beyond)
Unit V: CP-Violation in B-Decays (BELLE)

The B-Meson

History

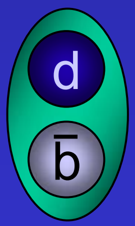
- 1977 Discovery of b-quark in $\Upsilon(1S)$ at FNAL (USA)
- 1978 $\Upsilon(1S)$ and $\Upsilon(2S)$ at DESY (Germany)
- 1982 First observation of B-Mesons at CESR (USA)
- 1983 Measurement of inclusive b lifetime at PEP & PETRA
- 1987 $B^0\,\overline{B}^0$ Oscillations discovered at DESY (Germany)
- 1992 Evidence of B_s
- 1993 Observation of time-dependent oscillations
- 1994 Measurement of exclusive B lifetime
- 1998 Discovery of B_c
- 2001 CP-Violation found at PEP-II (USA) and KEKB (Japan)
- 2004 direct CP-Violation established



Υ

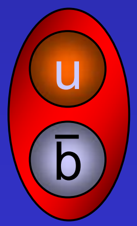
L=1

m(1S) = 9.46 GeV
m(2S) = 10.2 GeV
m(3S) = 10.4 GeV
m(4S) = 10.6 GeV



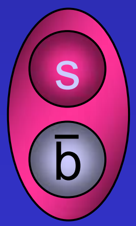
B^0 (B_d)

m = 5.28 GeV
$m(\Upsilon(4S))-2m(B^0)$ = 21 MeV
$c\tau$ = 460µm (!)



B^+ (B_u)

m = 5.28 GeV



B_s

m = 5.37 GeV
$m(\Upsilon(4S))-2m(B^0)$ = -159 MeV
$c\tau$ = 440µm

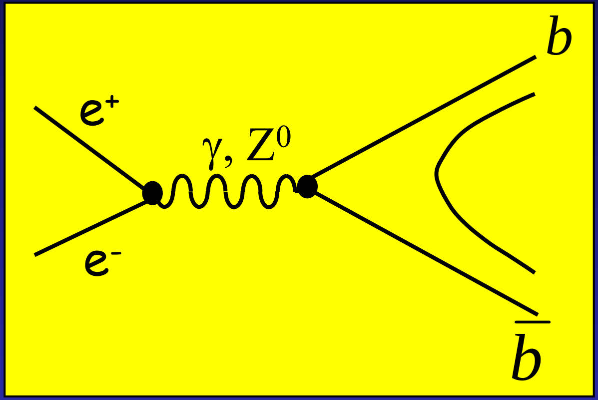
Production of B Mesons

1^{st} Question: How to produce the B-Mesons?

for precision measurements, a very large number of B-Mesons is needed

→ Method 1: an historical way – produce via Z_0 → bb

- by-product; experiments not designed (optimized) for B physics
- realized in: LEP experiments (Geneva, CH), SLD (Stanford, US)



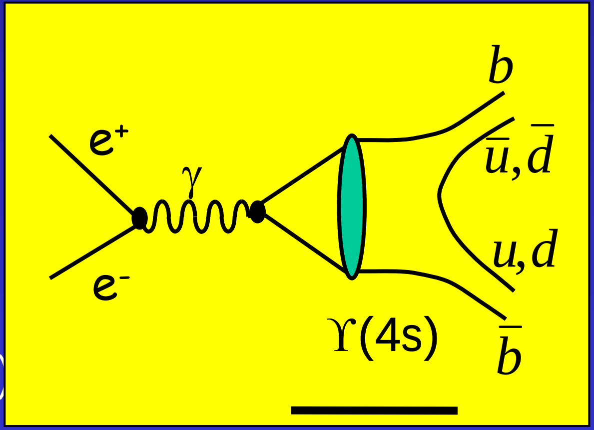
→ Method 2: the modern way – exploit the Υ(4S) resonance to enhance BB production

- pro: B-Mesons are produced just above threshold, small background; pure background can be easily studied by going slightly below threshold
- con: only $B_{u,d}$ are produced, no B_s
  - realized in: DORIS II (Hamburg, DE), CESR (Cornell, US)

↑ pioneers (ARGUS,CLEO)

PEP-II (Stanford, US) / KEKB (Tsukuba, JP)

↑ B-Factories (BaBar, Belle)



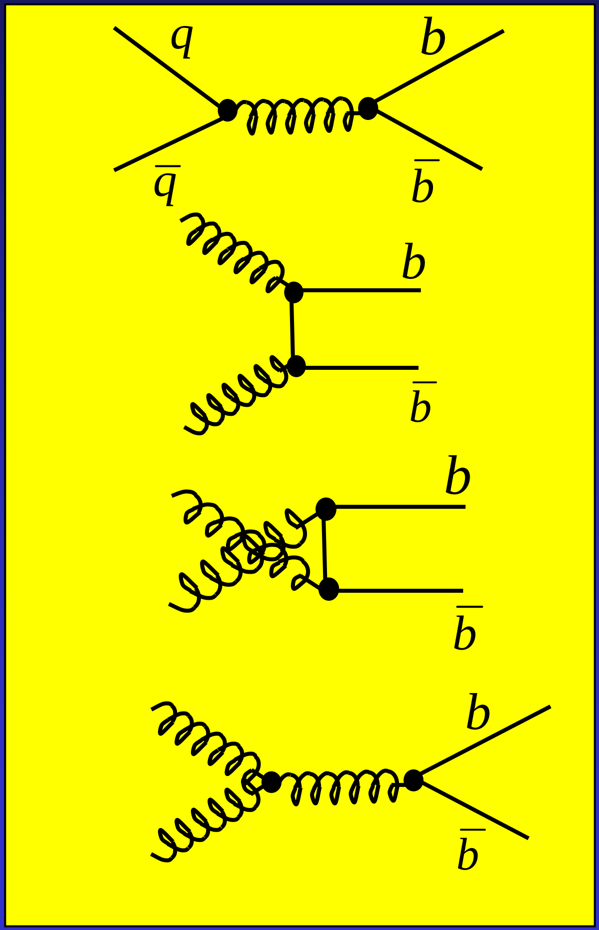
Production of B Mesons

1st Question: How to produce the B-Mesons?

for precision measurements, a very large number of B-Mesons is needed

→ Method 3: hadron colliders - smash hadrons at high energies

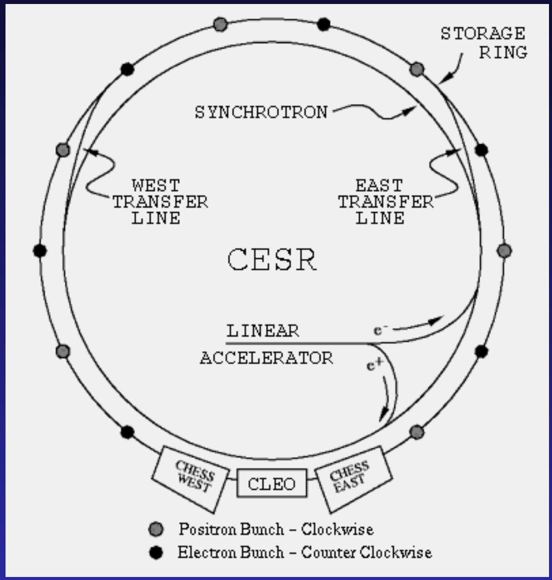
- pro: B-Mesons can be copiously produced in very large numbers
- con: large hadronic background
- realized in: CDF, DØ (Fermilab, US)
  future LHC experiments (especially LHCb)



Production of B Mesons

2nd Question: In which way produce the B-Mesons?

for lifetime measurements, a precise determination of the decay vertex is needed

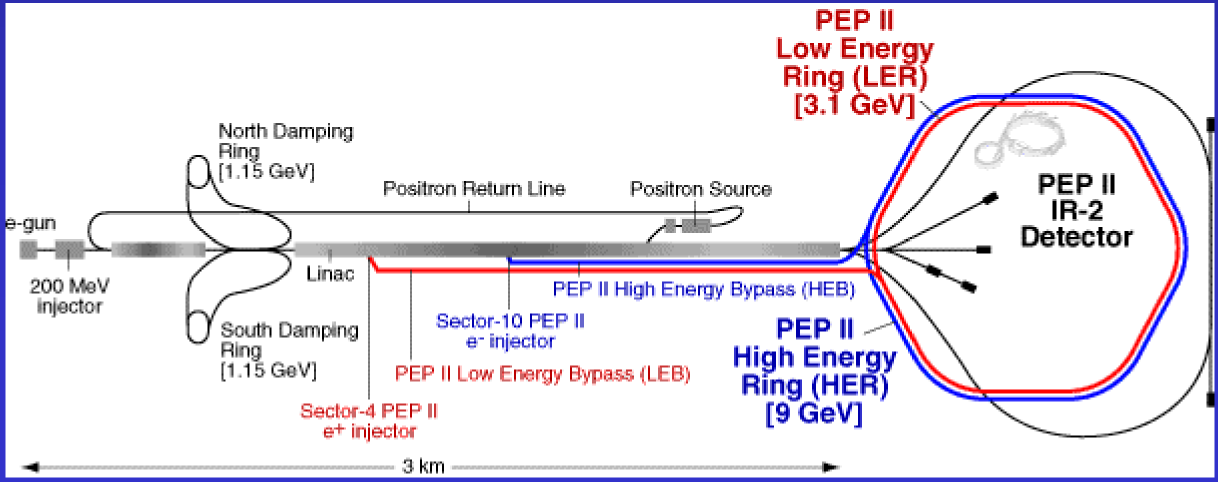


→ **Method 1: symmetric colliders** – beams have same energy

- if operating on the $\Upsilon(4S)$ resonance, B-mesons are almost at rest → hard to separate decay vertices
- realized in: CESR (Cornell, US), DORIS (Hamburg, DE)

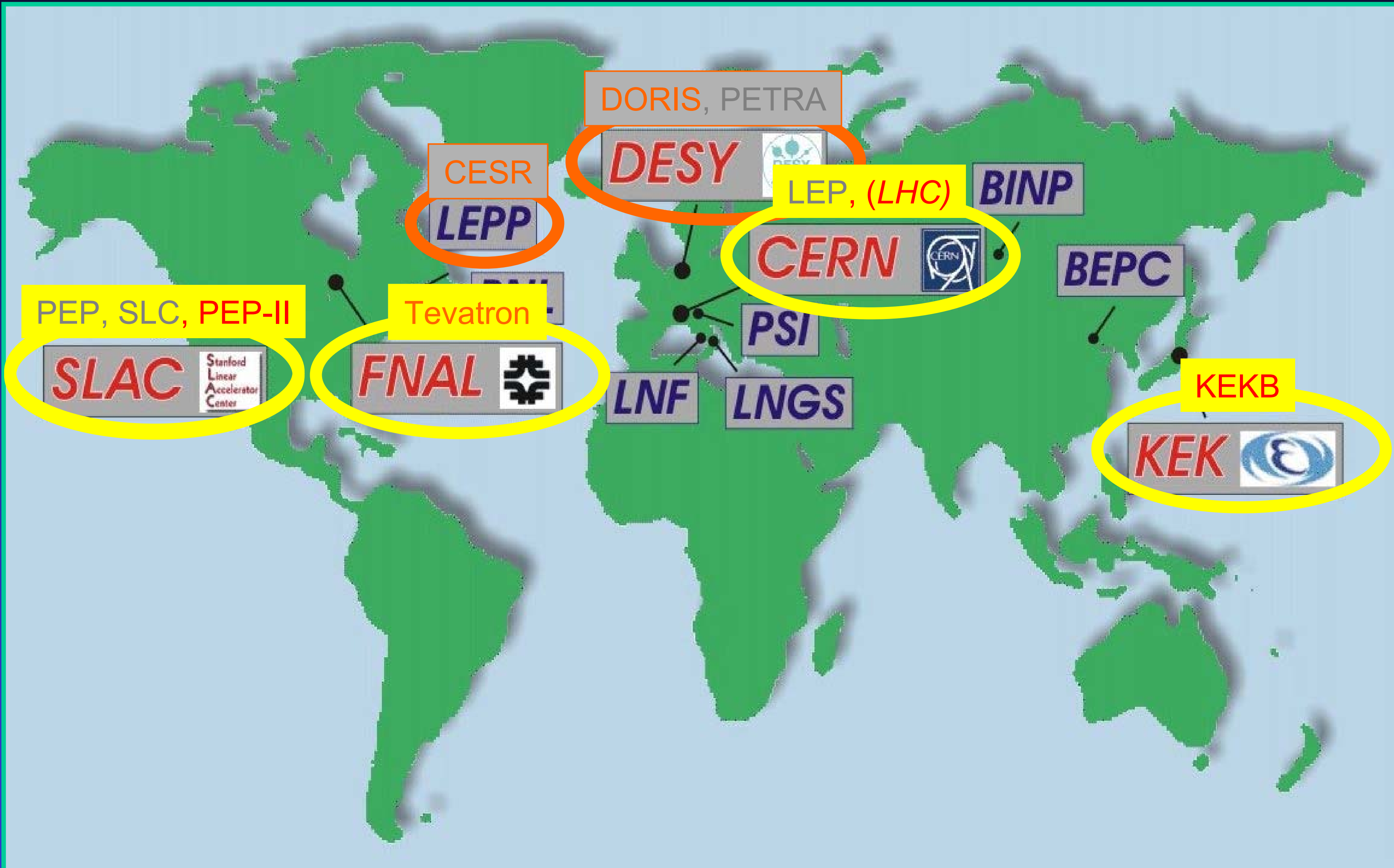
→ **Method 2: asymmetric colliders** – beams have different energy

- B-mesons are boosted in one favored direction, lifetime can be measured via high-resolution silicon vertex detectors
- realized in: PEP-II (Stanford, US) / KEKB (Tsukuba, JP)



Production of B Mesons

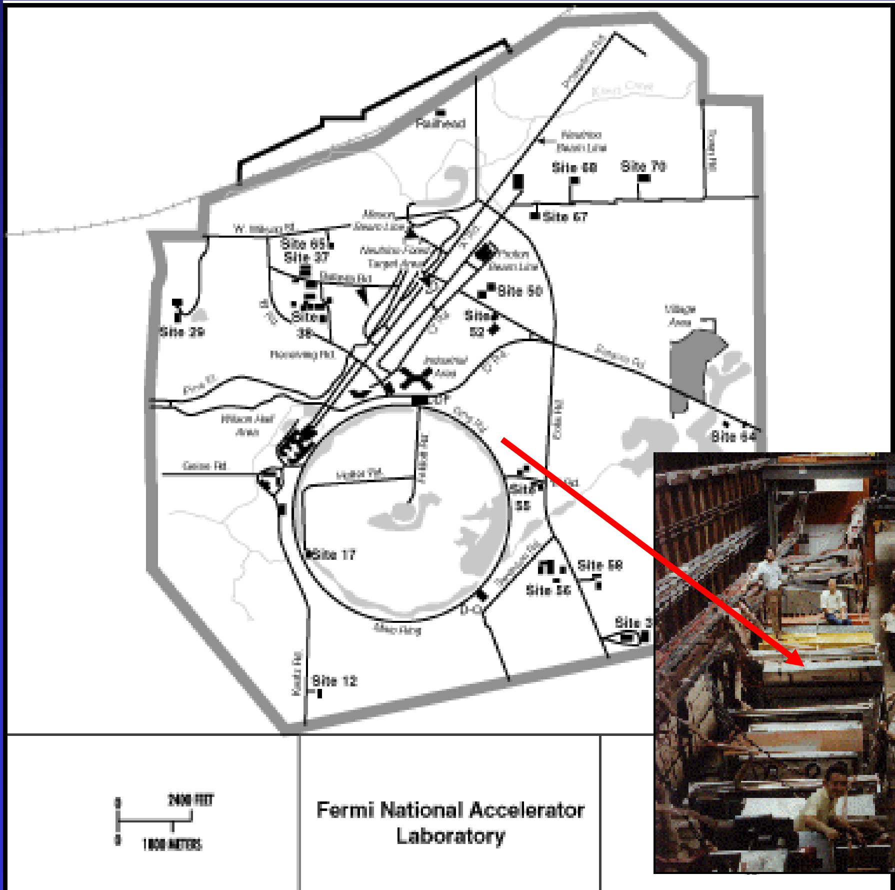
Overview of Colliders

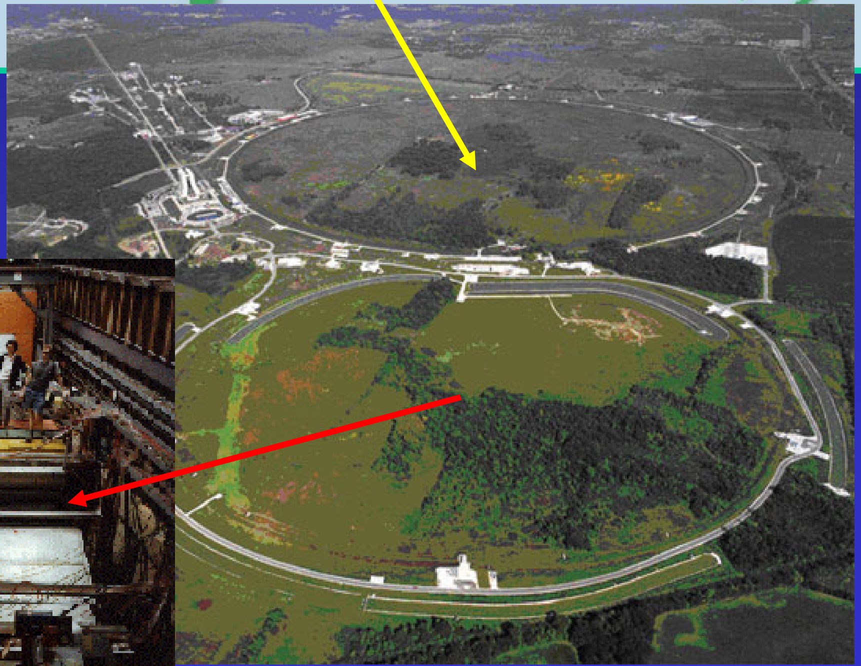


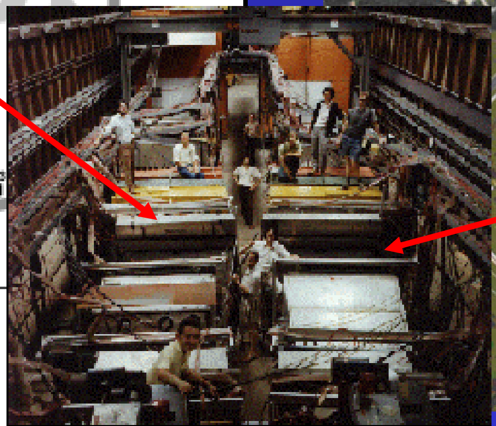
B Meson Experiments
The Past – First Discoveries

FNAL

- 1977 Discovery of b-quark in $\Upsilon(1S)$





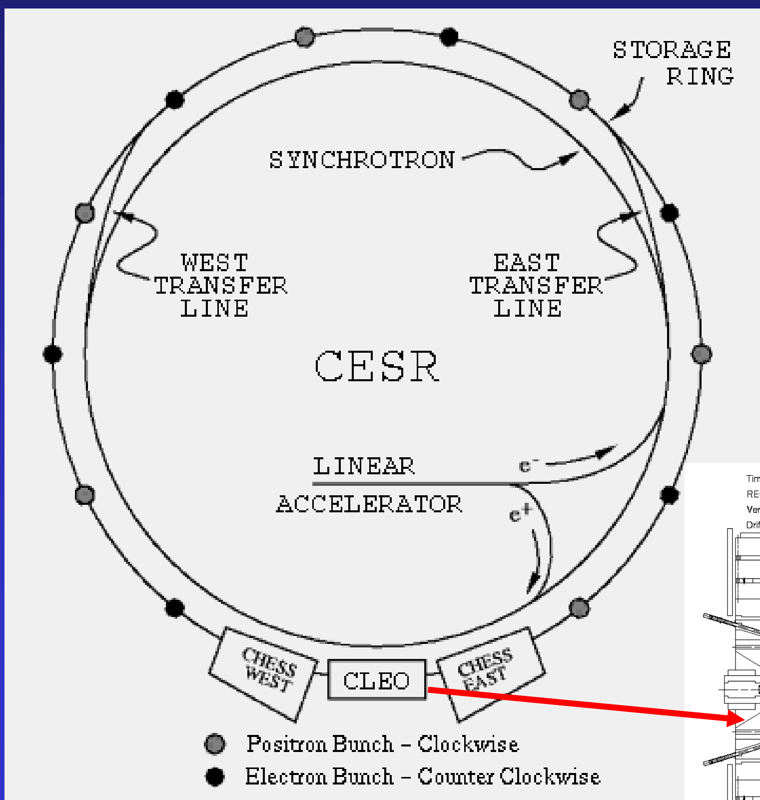


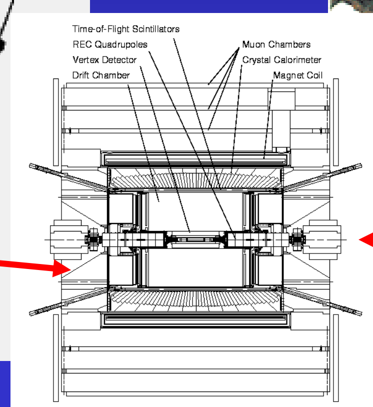
B Meson Experiments The Past – First Discoveries

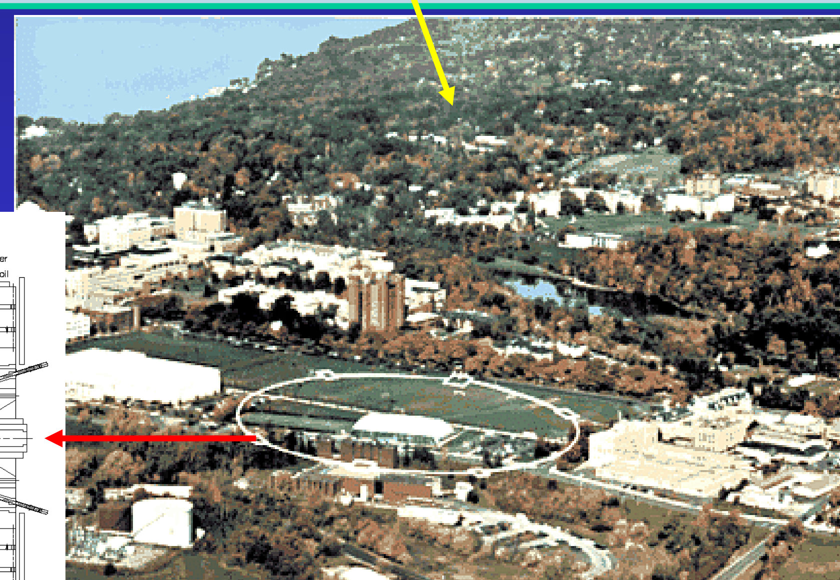
CLEO

1979 – 1989

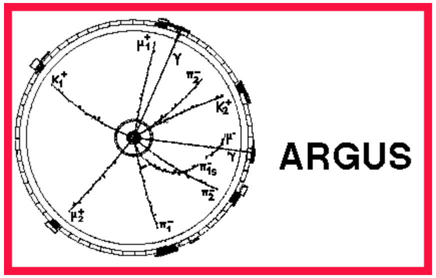
- 1982 Discovery of B-Meson
- 1989 upgraded to CLEO-II





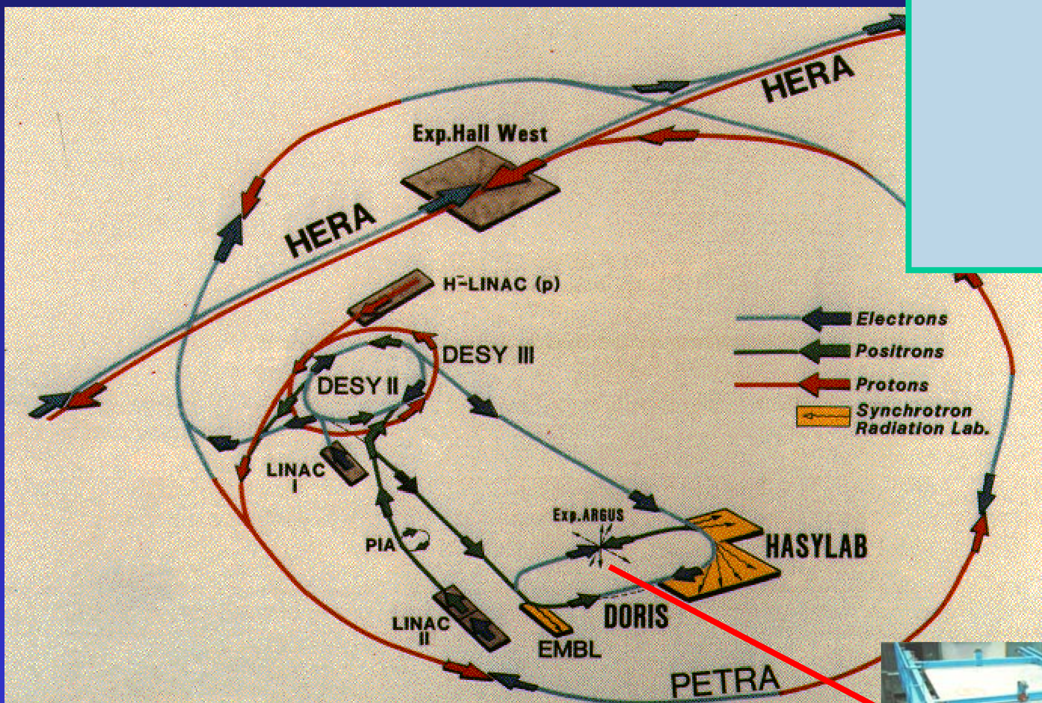


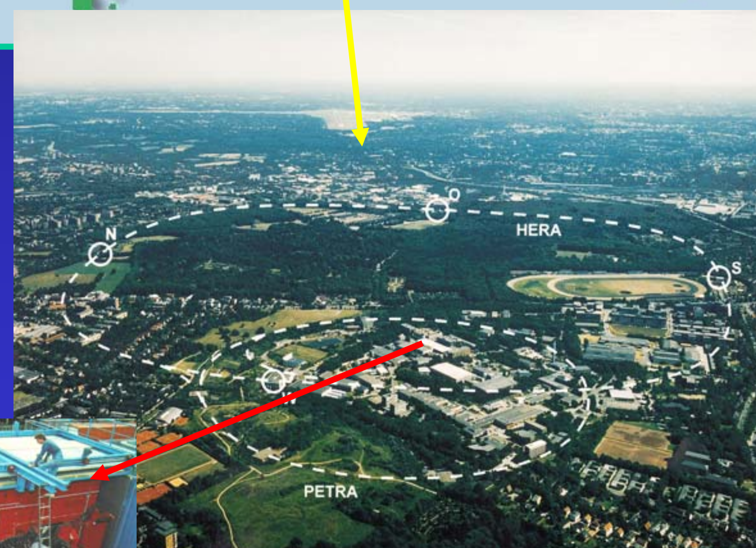
B Meson Experiments The Past – First Discoveries



1982 – 1993

- 1987 Discovery of $B\bar{B}$-Oscillations



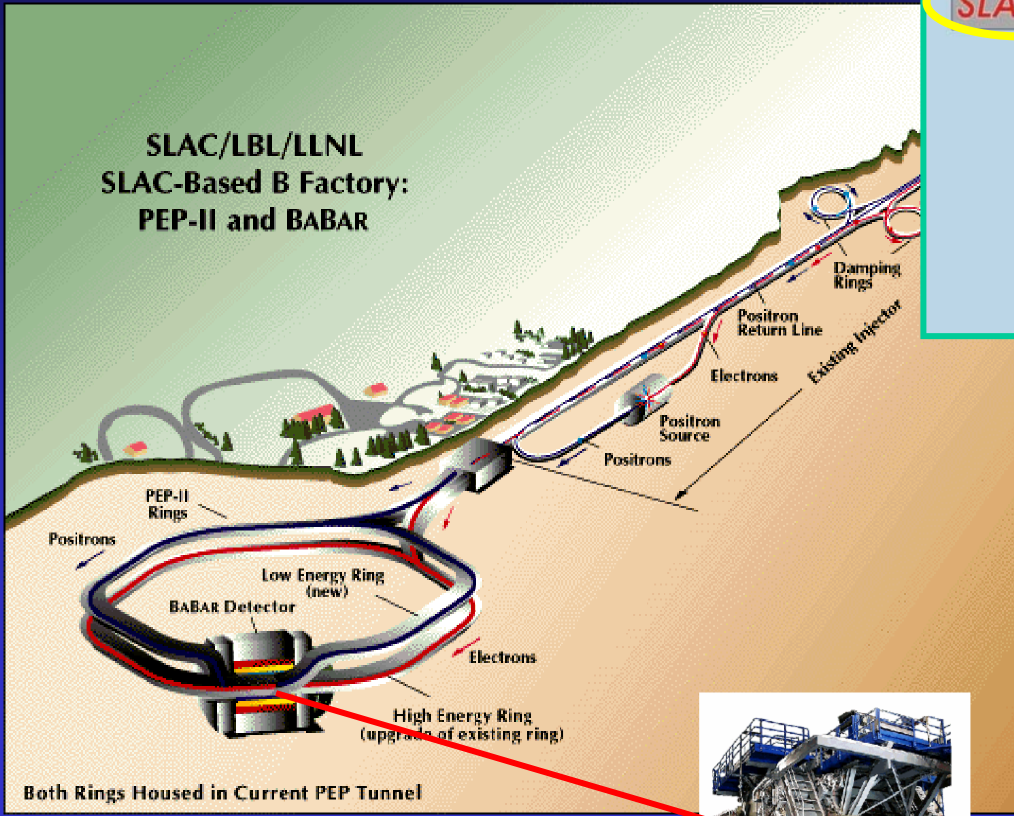


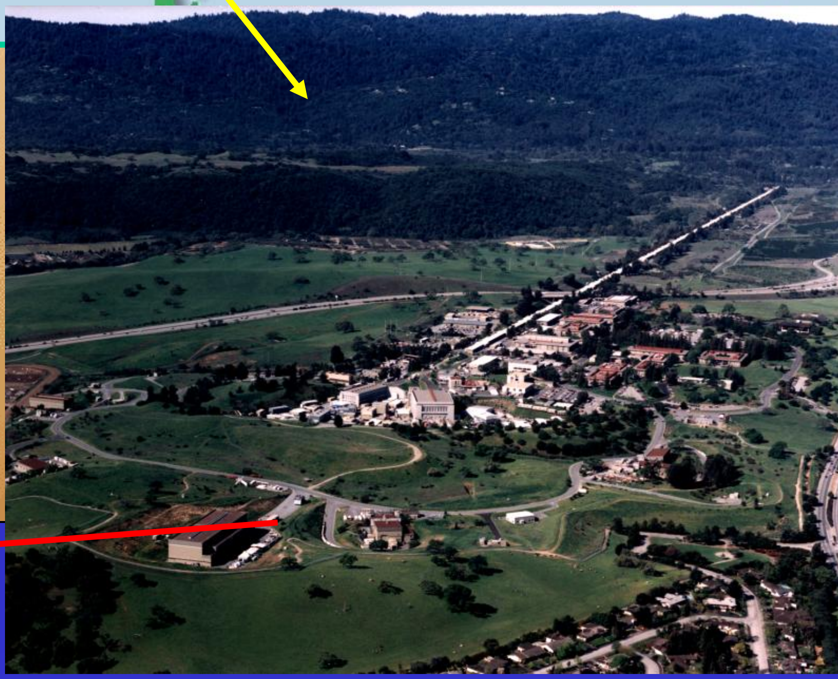
B Meson Experiments
The Present – B Factory Experiments

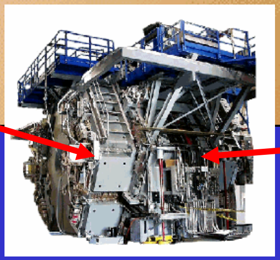
BABAR

2000 – now

- 2001 CPV in B-System
- 2004 dCPV in B-System





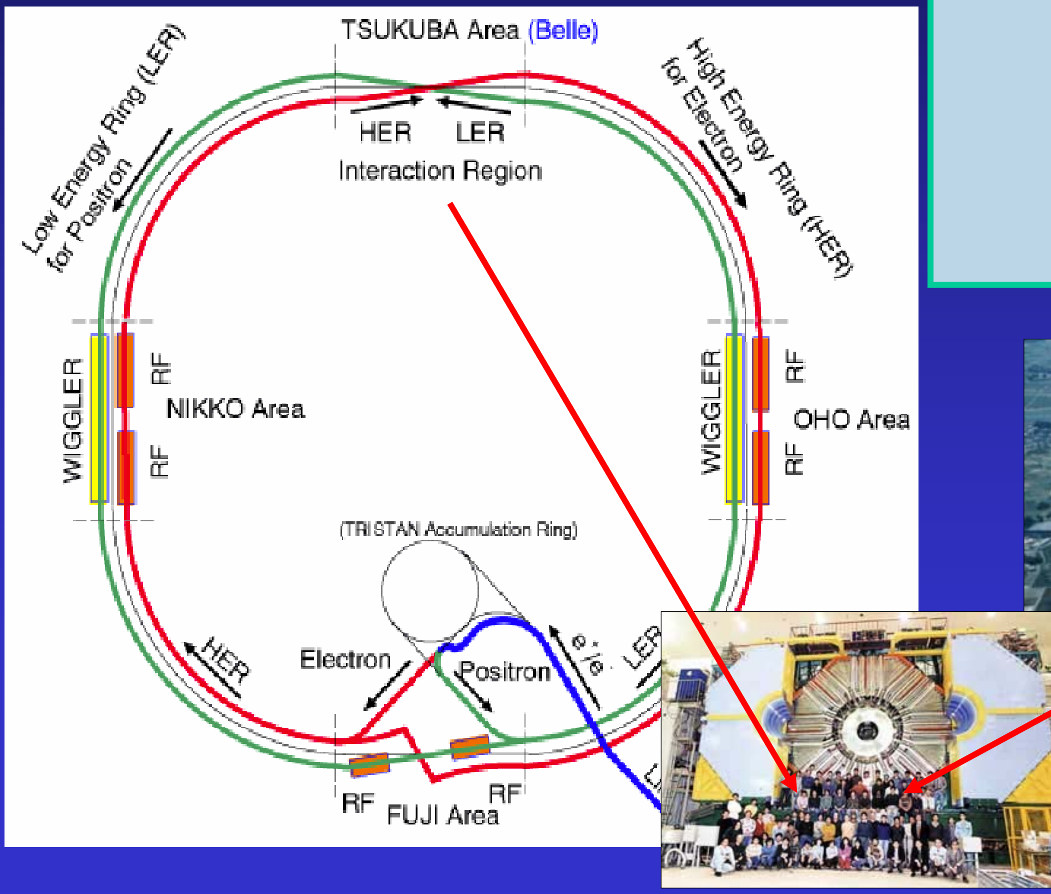


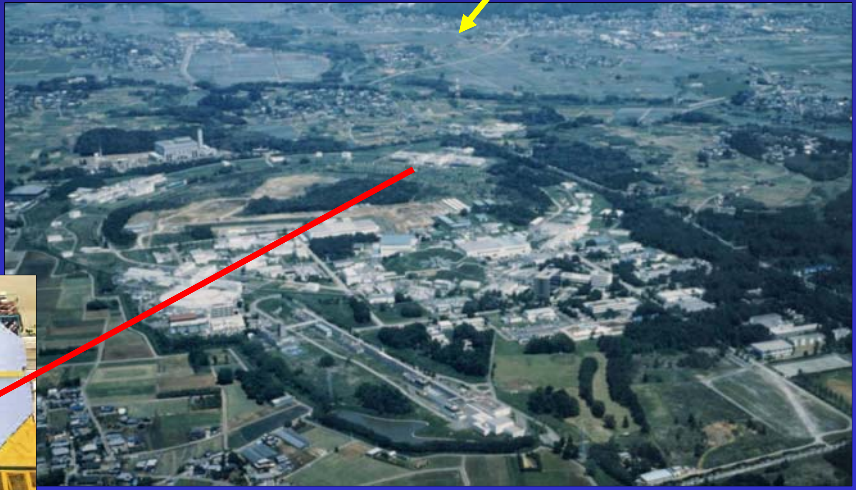
B Meson Experiments The Present – B Factory Experiments

BELLE

2000 – now

- 2001 CPV in B-System
- 2004 dCPV in B-System





The neutral B-Meson

Mass Eigenstates

$H_{eff} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = M - i/2\,\Gamma$ $H|B\rangle = id/dt|B\rangle$ $|B\rangle = \begin{pmatrix} B_0 \\ \overline{B}_0 \end{pmatrix}$

decomposition of non-hermitian H using two hermitian matrices M, Γ

Phase convention: $CP|B_0\rangle = |\overline{B}_0\rangle$

CPT-Theorem → $H_{11} = H_{22}$

→ Mass Eigenstates $|B_{L(ight), H(eavy)}\rangle = p|B_0\rangle \pm q|\overline{B}_0\rangle$ normalization: $|p|^2+|q|^2=1$

Eigenvalues $H_{H,L} = H_{11} \pm \sqrt{H_{12}H_{21}}$ $q/p = -(H_H-H_L)/2H_{12}$

note: CP eigenstate if (and only if) $q/p = \pm 1$

time evolution: $|B_{H,L}\rangle(t) = e^{-iH_{H,L}t}\,|B_{H,L}\rangle(0) = e^{-\Gamma_{H,L}/2t}e^{-iM_{H,L}t}\,|B_{H,L}\rangle(0)$

→ 2 neutral B-Mesons (one heavier, one lighter), decaying with (generally) different decay constants

But what is actually observed in experiment?

→ the experimental "character" of the B depends on the actual values of above parameters

→ the different "character" of the K is due to different values of those parameters

… but before taking a closer look on these points, let's further expand the picture:

The CKM Hierarchy

CKM Matrix V_{CKM}

- governs conversion between up- and down-type quarks in the SM
- unitary within SM: $V^{+}V = VV^{+} = 1$ → defined by 9 Parameters (3 angles, 6 phases)
- 5 phases can be gauged to zero by appropriate definition of the 5 relative phases of the 6 u,c,t / d,s,b quarks
- CP Violation in the SM governed by the single remaining phase
- note: this phase is not small, i.e. CP violation is not small in the SM!
- different parametrizations of V possible, that of Wolfenstein reflects its hierarchical structure:

$$V_{CKM} = \begin{pmatrix} u \leftrightarrow d & u \leftrightarrow s & u \leftrightarrow b \\ c \leftrightarrow d & c \leftrightarrow s & c \leftrightarrow b \\ t \leftrightarrow d & t \leftrightarrow s & t \leftrightarrow b \end{pmatrix}$$

The different Characters of the B^0- and K^0-Meson

	B^0-Meson	K^0-Meson
mean mass m	5279 MeV/c²	497 MeV/c²
mass difference Δm	$O(10^{-10})$ MeV/c²	$O(10^{-12})$ MeV/c²
life time	τ_H = 1.5ps τ_L = 1.5ps	τ_H = 51800.0ps τ_L = 89.6ps

→ practically same life time for B^0, but big difference for K^0
why? see below!
consequence: K^0 more naturally classified by life time: $K_{L(ong\text{-}lived)}$, $K_{S(hort\text{-}lived)}$; K_L can be easily observed experimentally by „just waiting“ for K_S component to decay away; no such easy way for B mesons!
→ lifetime of B^0 rather long for its large mass
why? hierarchical structure of V_{CKM} highly suppresses b→c,u transitions

	B^0-Meson	K^0-Meson
$\lvert q/p \rvert$	$\cong 1$ this is a consequence of $\Gamma_{12} << M_{12}$	$\cong 1$
$\mathrm{Im}(q/p)$	$O(1)$	$O(10^{-3})$

→ $K^0_{S,L}$ almost CP eigenstates (see slide 3), $B^0_{H,L}$ clearly not
why? CP violation in 2nd generation suppressed due to CKM hierarchy
consequence: long lifetime of K_L, since CP is almost conserved, and the large $K \rightarrow \pi\pi$ channel is CP-forbidden

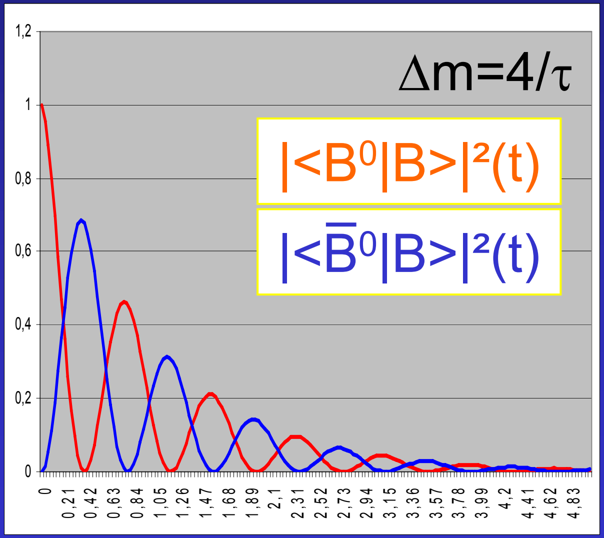
How B^0-Mesons show up in the Experiment

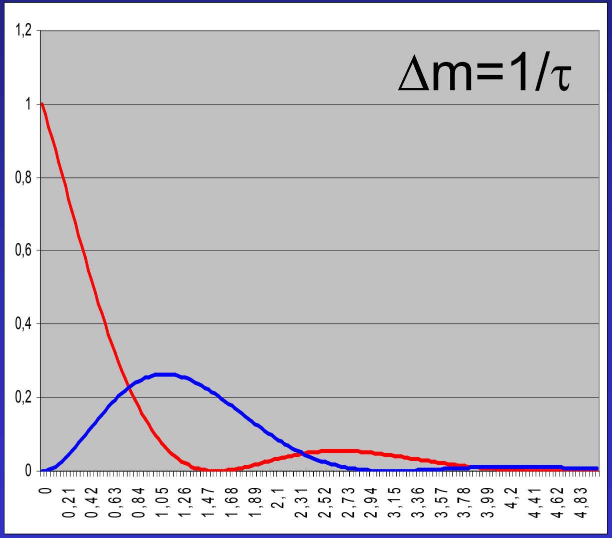
- B^0-Mesons are produced via strong interactions, therefore in the strong eigenstates $B^0/\bar{B}^0$
- this corresponds to superpositions of mass eigenstates:

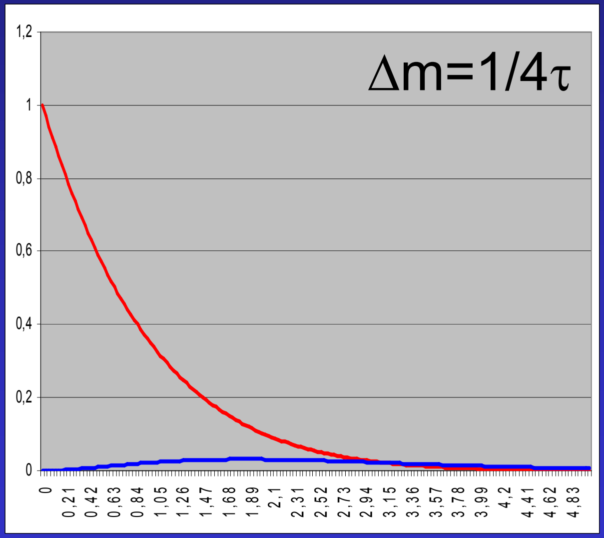
$$|B^0\rangle \sim |B_H\rangle + |B_L\rangle \qquad |\bar{B}^0\rangle \sim |B_H\rangle - |B_L\rangle$$

- therefore, generally interference occurs; for a B^0 at $t=0$, due to $\tau_H \cong \tau_L$

$$|B\rangle(t) = e^{-t/2\tau} e^{-imt} \left[\cos(\Delta m/2 \cdot t)\, |B^0\rangle + i q/p \cdot \sin(\Delta m/2 \cdot t)\, |\bar{B}^0\rangle \right]$$







- note „lucky coincidence“ $\Delta m \cong 0.7/\tau$ → oscillation time similar to decay time (if faster, experimental time resolution would be a problem; if slower, particles would decay before effect becomes visible)

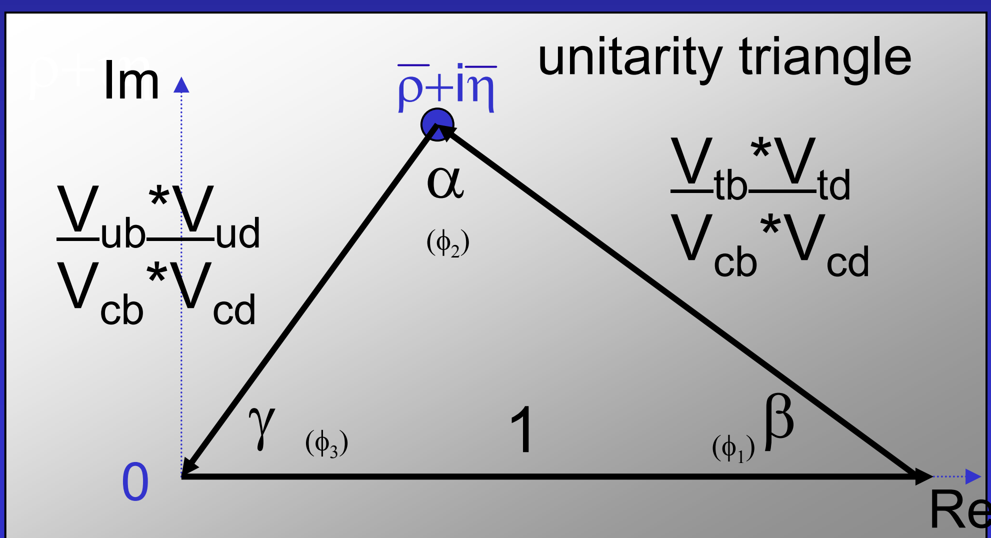
CP Violation with B-Mesons

CKM-Matrix

$$\begin{array}{c|ccc} & d & s & b \\ \hline u & & & \\ c & & \left(\begin{matrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{matrix}\right) & \\ t & & & \end{array}$$

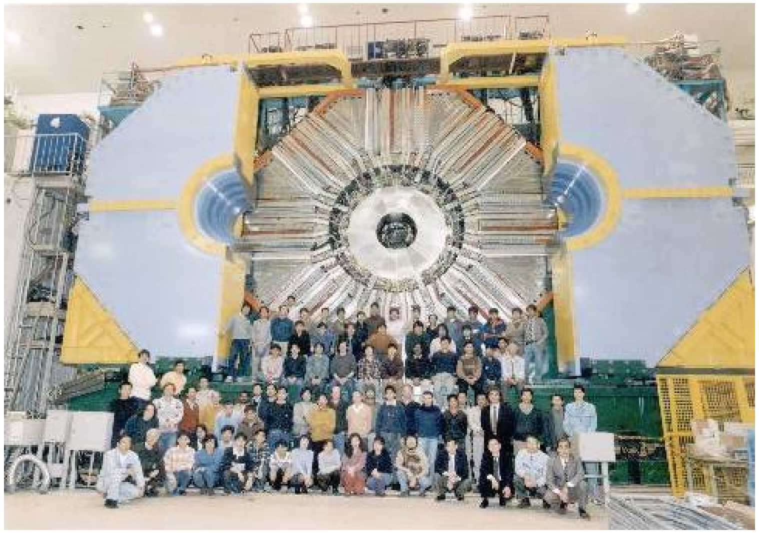
Unitarity $V^{+}V=1 \rightarrow V_{ub}{}^{*}V_{ud}+V_{cb}{}^{*}V_{cd}+V_{tb}{}^{*}V_{td} = 0$

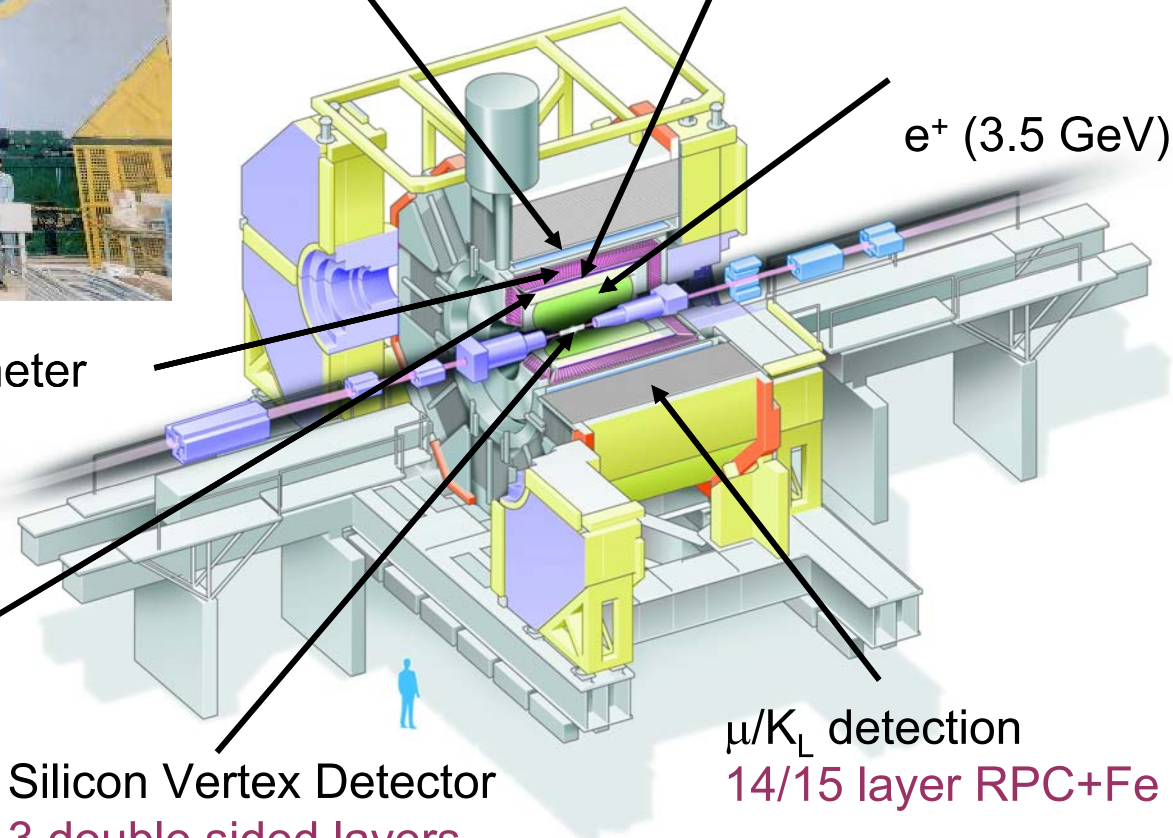
$$\rightarrow \underbrace{\frac{V_{ub}{}^{*}V_{ud}}{V_{cb}{}^{*}V_{cd}}}_{-(\bar{\rho}+i\bar{\eta})} + 1 + \underbrace{\frac{V_{tb}{}^{*}V_{td}}{V_{cb}{}^{*}V_{cd}}}_{-(1-\bar{\rho}-i\bar{\eta})} = 0$$



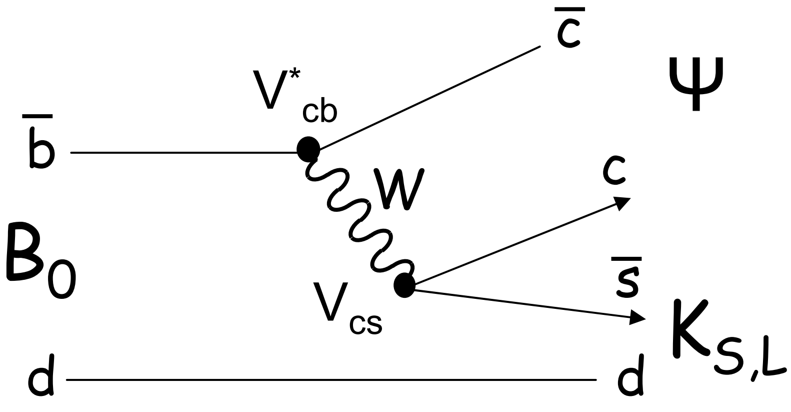
- area of triangle is a measure of CP Violation induced by CKM
- it is completely determined by just one parameter
- independent measurements of sides and angles of the triangle check the consistency of the SM, and can reveal the presence of New Physics

B Meson Experiments
The Present – B Factory Experiments





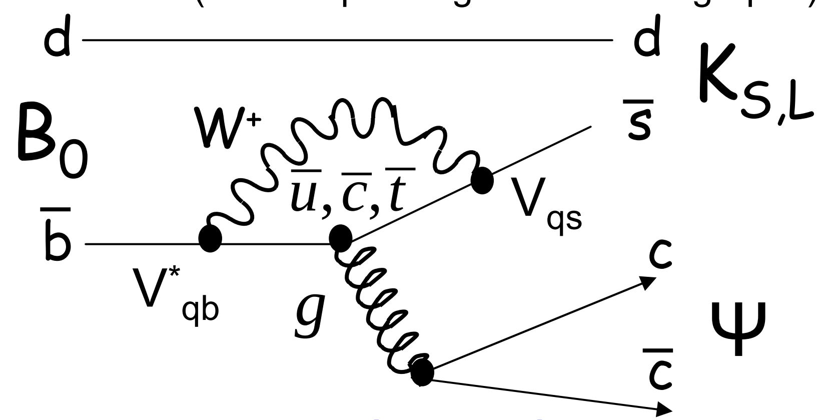
The Analysis: $B \rightarrow \Psi K_{S,L}$ (quark transition $\bar{b} \rightarrow \bar{c}c\bar{s}$)



tree graph

dominating this decay

(+ corresponding electroweak graphs)



penguin graph

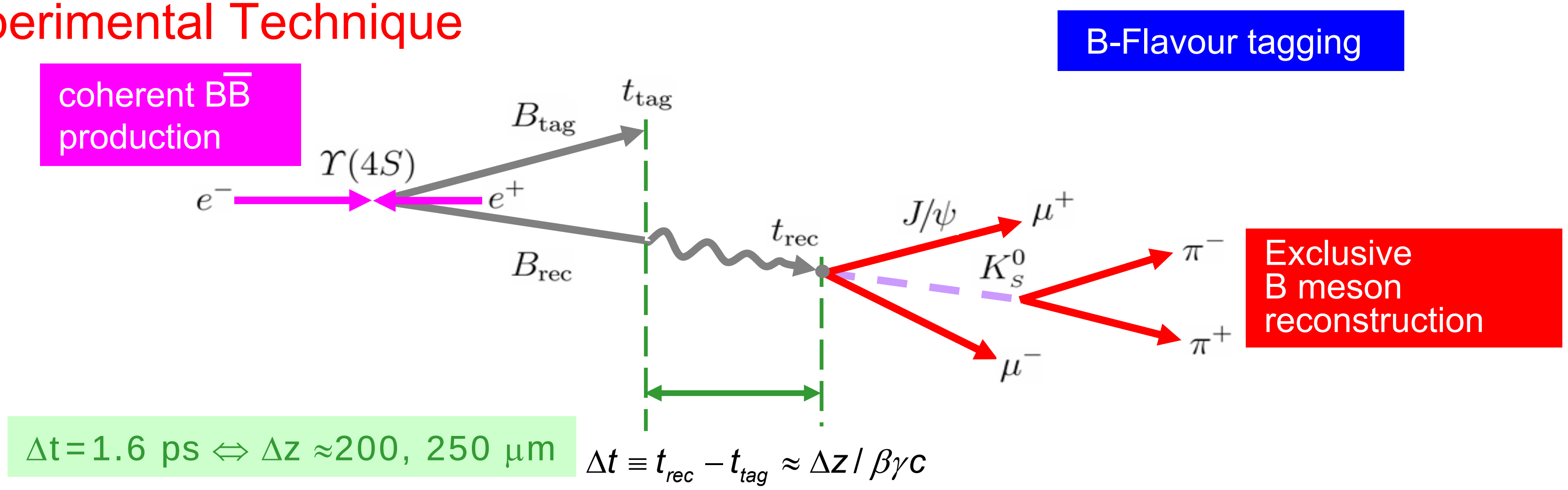
contributions not proportional to $V^*_{cb}V_{cs}$ suppressed to ~$O(10^{-2})$ by $V^*_{ub}V_{us} / V^*_{cb}V_{cs} \sim \lambda^2$

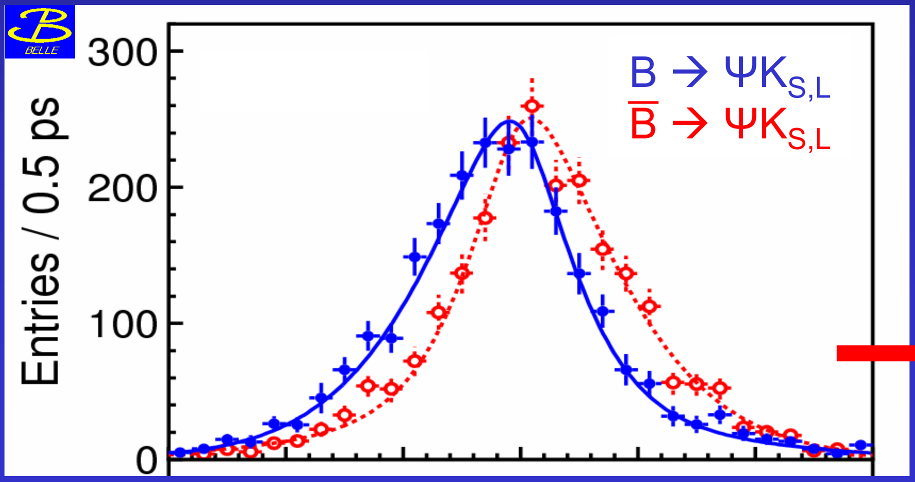
- $$\frac{\Gamma(B^0 \rightarrow \Psi K_s) - \Gamma(\bar{B}^0 \rightarrow \Psi K_s)}{\Gamma(B^0 \rightarrow \Psi K_s) + \Gamma(\bar{B}^0 \rightarrow \Psi K_s)} = A^{dir}_{CP}\cos(\Delta mt) + A^{mix}_{CP}\sin(\Delta mt)$$
- decay into CP eigenstate, governed by a single amplitude ~ $V^*_{cb}V_{cs}$
- therefore, no direct CPV contribution: $A^{dir}_{CP} \cong 0$
- amplitude of sine is given by: $A^{mix}_{CP} = -\sin 2\beta$

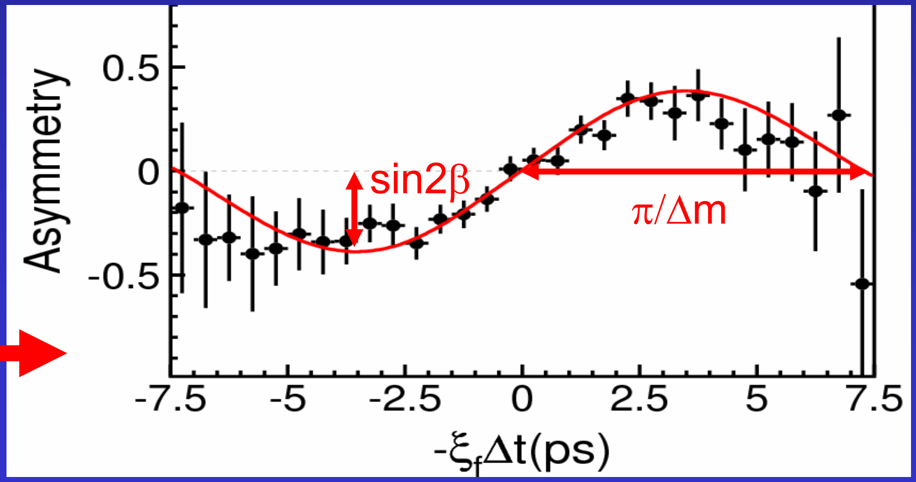
→ golden channel for measurement of $\sin 2\beta$

The Analysis: $B \rightarrow \Psi K_{S,L}$ (quark transition $\bar{b} \rightarrow \bar{c}c\bar{s}$)

Experimental Technique

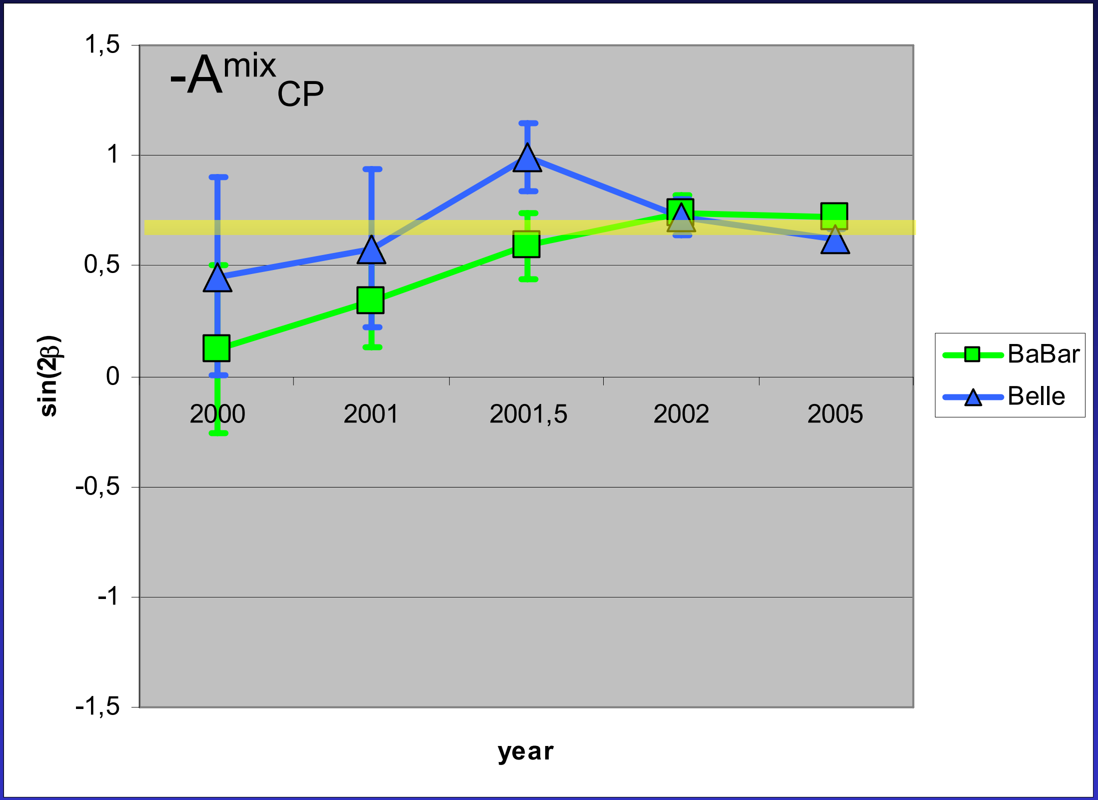


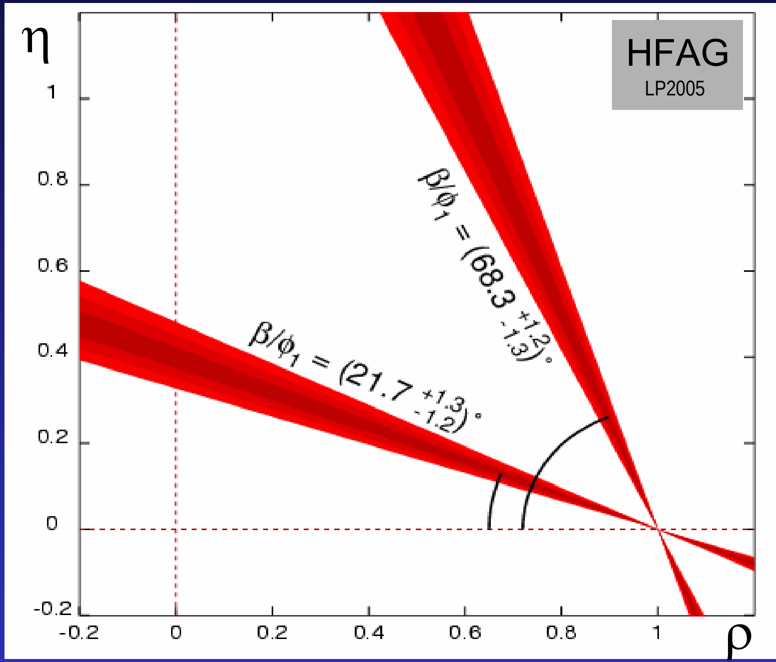




The Analysis: $B \rightarrow \Psi K_{S,L}$ (quark transition $\bar{b} \rightarrow \bar{c}c\bar{s}$)

History of Experimental Results

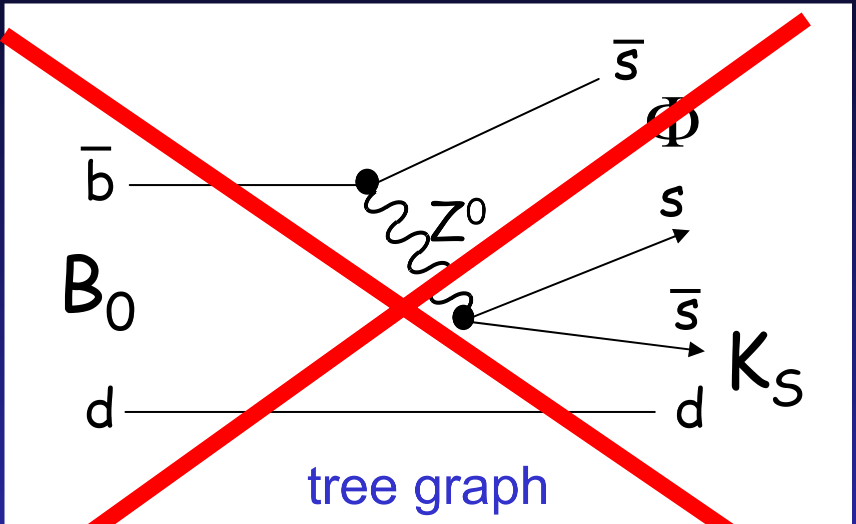




- HFAG Summer 2005 Average : $\sin(2\beta) = 0.685 \pm 0.032$
- SM prediction using all experimental information *except* ΨK_S: 0.68 ± 0.18
- no indication of direct CPV

➔ impressive agreement with SM predictions!

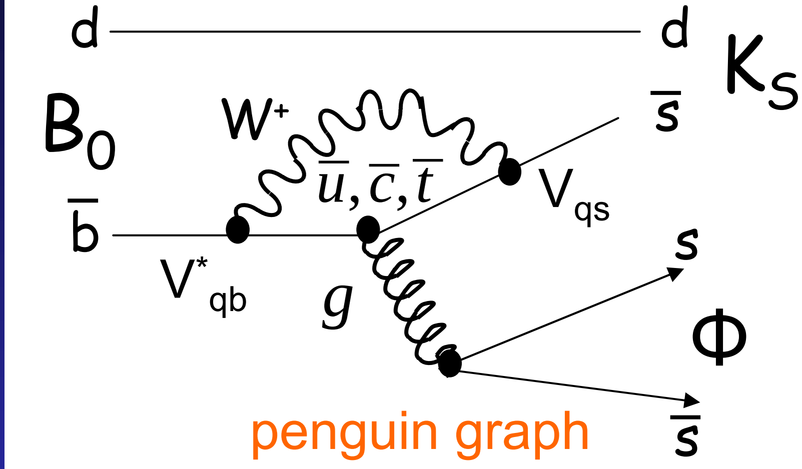
The Analysis: $B \rightarrow \Phi K_S$ (quark transition $\bar{b} \rightarrow \bar{s}q\bar{q}$)



tree graph

cannot generate contributions to b → sss

(+ corresponding electroweak graphs)



penguin graph

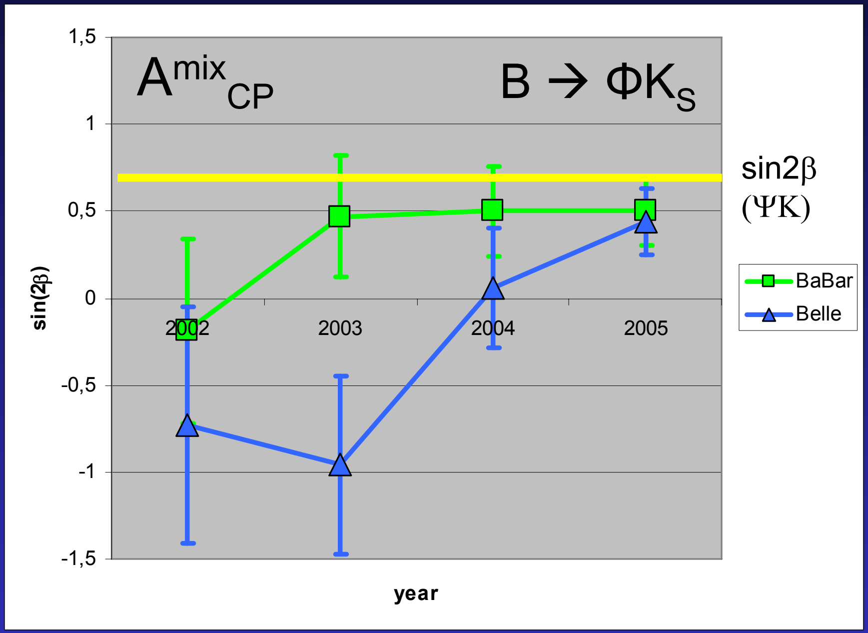
contribution proportional to $V^*_{ub}V_{us}$ suppressed to $\sim O(10^{-2})$ by $V^*_{ub}V_{us} / V^*_{cb}V_{cs} \sim \lambda^2$

- remember slide #10: $$\frac{\Gamma(B^0 \rightarrow \Phi K_s) - \Gamma(\bar{B}^0 \rightarrow \Phi K_s)}{\Gamma(B^0 \rightarrow \Phi K_s) + \Gamma(\bar{B}^0 \rightarrow \Phi K_s)} = A^{dir}_{CP}\cos(\Delta mt) + A^{mix}_{CP}\sin(\Delta mt)$$
- decay into CP eigenstate, governed by a single amplitude $\sim V^*_{cb}V_{cs}$
- therefore, no direct CPV contribution: $A^{dir}_{CP} \cong 0$
- amplitude of sine is given by: $A^{mix}_{CP} = \sin 2\beta$

→ penguin dominated, sensitive to New Physics in loop!

The Analysis: $B \rightarrow \Phi K_S$ ($\eta' K_S$) (quark transition $\bar{b} \rightarrow \bar{s}q\bar{q}$)

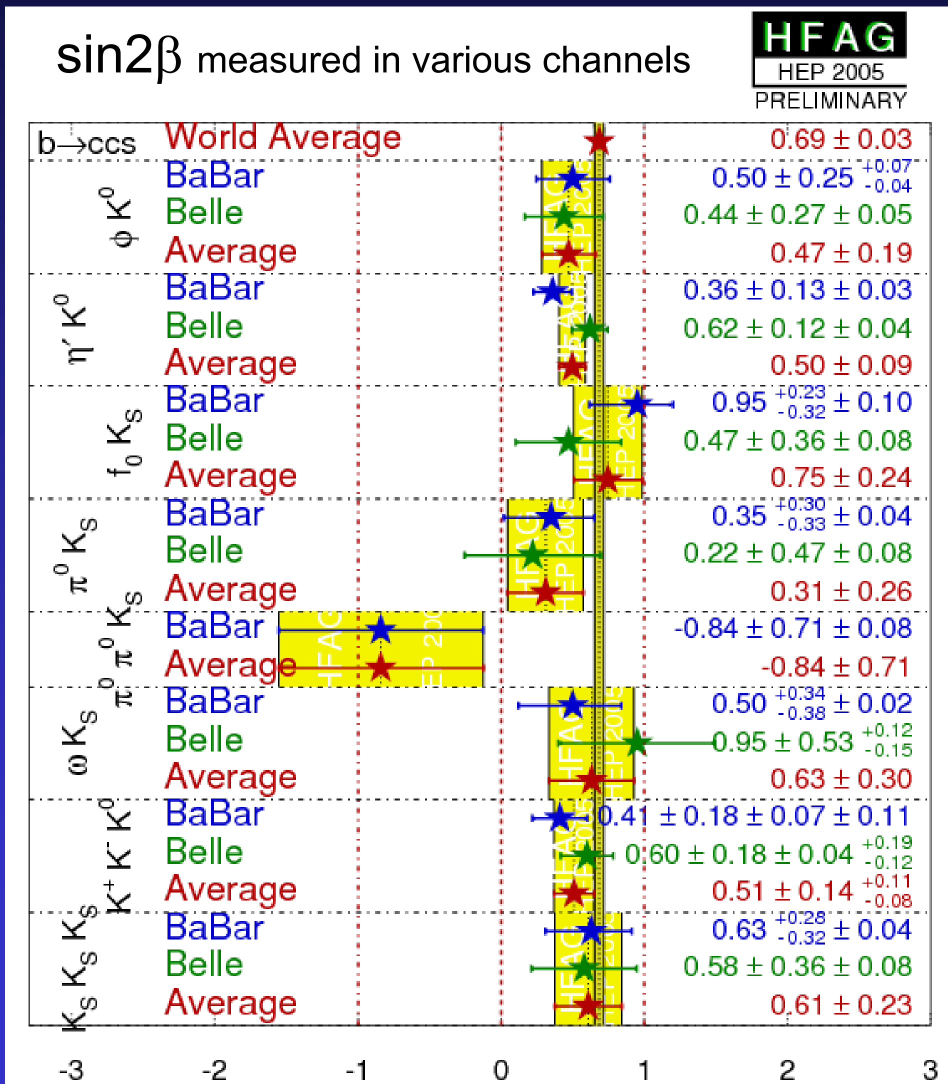
History of Experimental Results



- agreement between BaBar and Belle improved over the years
- A^{dir}_{CP} compatible with zero (no indication of direct CPV)

The Analysis: $B \rightarrow XK_S$ (quark transition $\bar{b} \rightarrow \bar{s}q\bar{q}$)

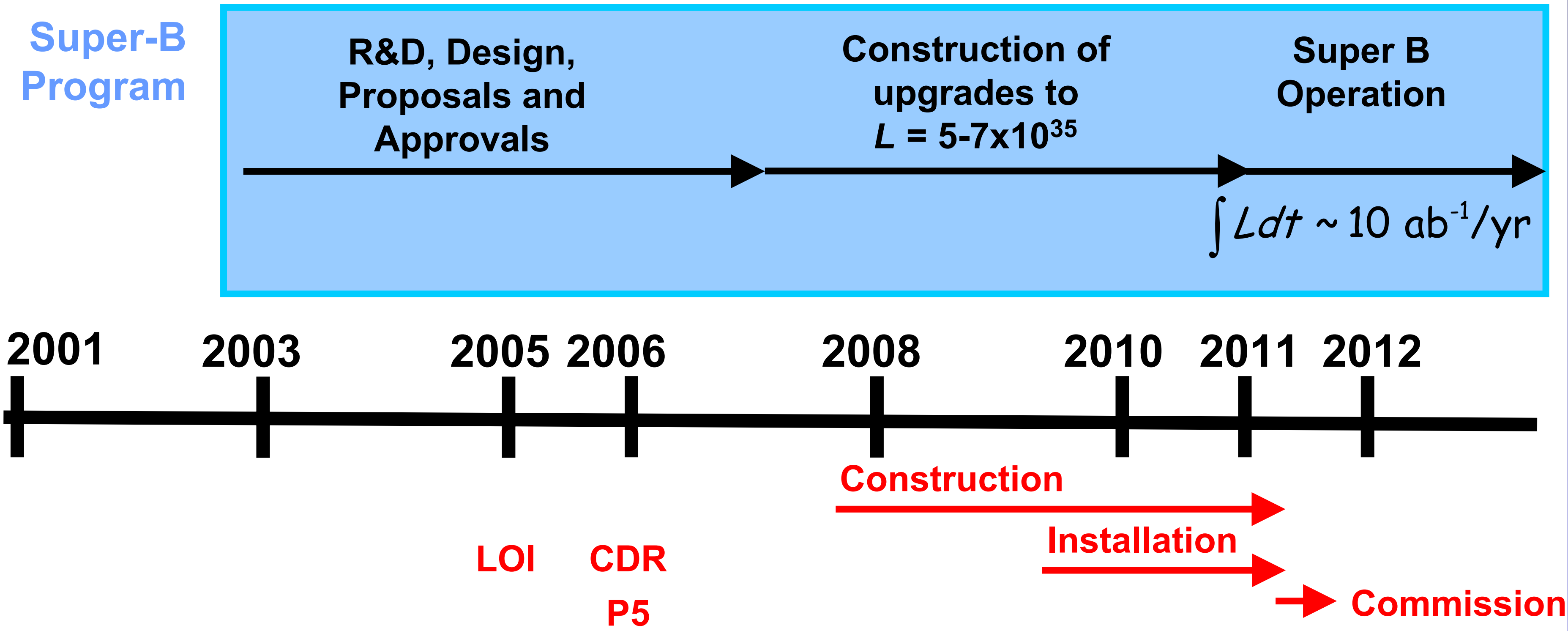
Overview of various channels



→ not incompatible with SM (though systematically lower), future will settle questions of NP!

Outlook – the not that near future: *starting ≥ 2012?*
Super Factories „the luminosity frontier“

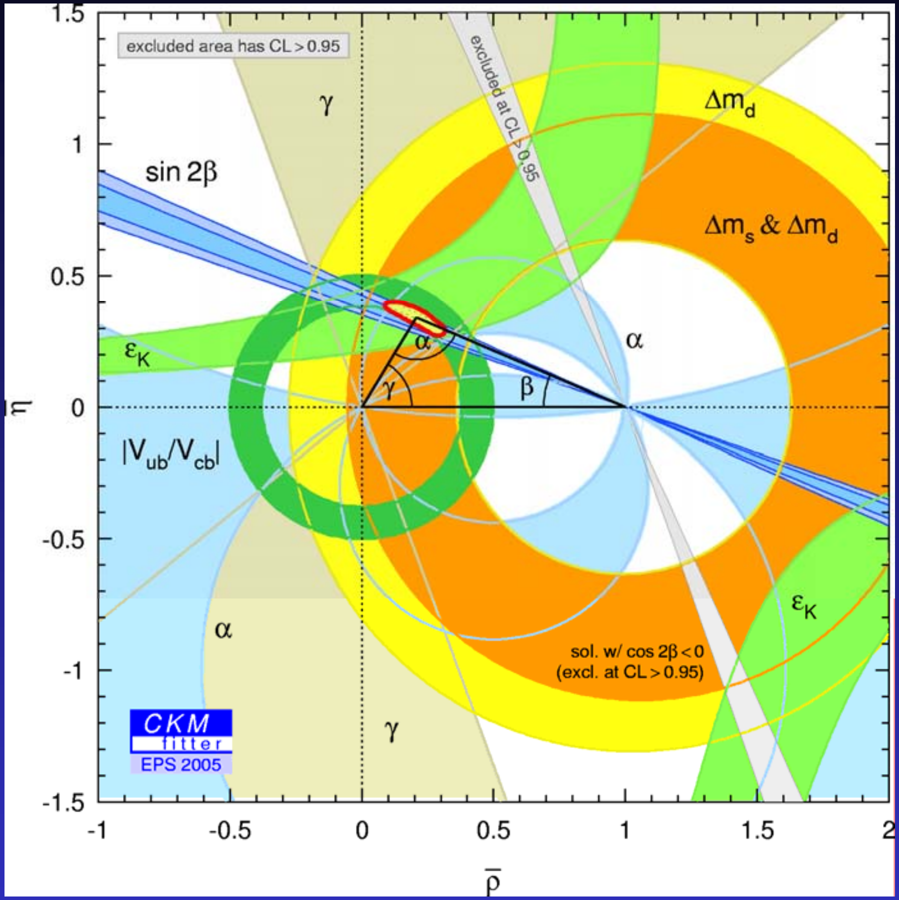
Possible Timeline for Super B Program



And the conclusion is...

- B-Mesons opened the door to exciting new physics
- so far, the SM gloriously weathers another precision check
- still, New Physics might be just around the corner...

- The B-Factories BaBar and Belle will study hundreds of millions of B-mesons more over the next years
- LHC will deluge©J.Ellis us with some orders of magnitude more of data, ready for any surprise that is waiting for discovery
- and Super-B-Factories are in the pipeline for precision measurements of whatever LHC will find



Hope you got some overview of the interesting field of particle physics!

→ **Hope to meet you at CERN, KEK or some other lab one day!!**

- END of Unit V -